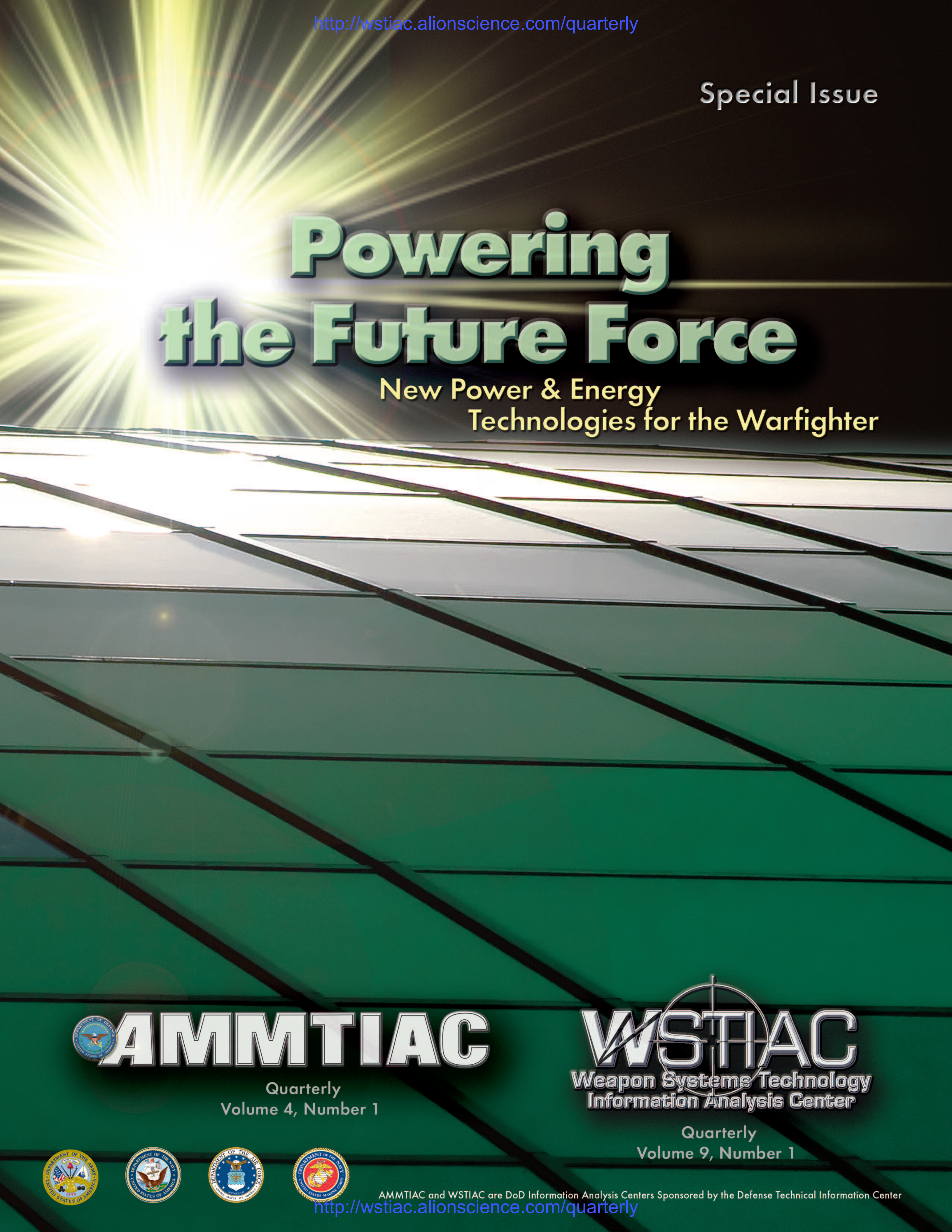

Special Issue

Powering the Future Force

New Power & Energy Technologies for the Warfighter

AMMTIAC

Quarterly
Volume 4, Number 1

WSTIAC

Weapon Systems Technology Information Analysis Center

Quarterly
Volume 9, Number 1

AMMTIAC and WSTIAC are DoD Information Analysis Centers Sponsored by the Defense Technical Information Center

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 JAN 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **WSTIAC Quarterly, Vol. 9, No. 1 - Powering the Future Force; New Power & Energy Technologies for the Warfighter**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **WSTIAC Weapon Systems Technology Information Analysis Center, Rome, NY**	8. PERFORMING ORGANIZATION REPORT NUMBER **WSTIAC-V9-N1**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Defense Technical Information Center, Ft Belvoir, VA**	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
This issue of the WSTIAC Quarterly features multiple articles on New Power & Energy Technologies for the Warfighter. Included the WSTIAC Calendar of Events and the Directors Corner. Details on several Training Courses sponsored by WSTIAC are also included in this issue.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**92**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Energy is a force multiplier – and a limitation. Energy efficiency increases maneuverability, agility, and makes our forces more expeditionary. However, our new systems require ever increasing energy, during a time when getting fuel to forward locations is considered an operation, with vulnerable supply lines requiring additional security forces. The Secretary of Defense recognized this tension three years ago when he established the DoD Energy Security Task Force.

There's still much work to do, but the DoD is on the right path.

The DoD Energy Security Task Force was charged with making recommendations on increasing energy efficiency, reducing dependence on foreign oil, and integrating energy efforts across the Department. The Task Force included senior leaders in the Office of the Secretary of Defense, the Services and the Defense Advanced Research Projects Agency from all functional areas with a stake in energy – installations and environment, logistics, technology, acquisition, policy, comptroller and the joint staff. Taking a holistic, systems approach, the Task Force explored energy options across the spectrum of supply, demand and assured distribution to ensure the enterprise understands the interdependencies of energy-related decisions.

The Task Force developed a strategic plan, providing a framework for energy management across DoD, with Deputy Secretary-approved strategic outcomes:

1. Maintain or enhance operational effectiveness by reducing total force energy demands.
2. Increase energy strategic resilience by developing alternative/assured fuels and energy.
3. Enhance operational and business effectiveness by institutionalizing energy solutions in DoD planning and business processes.
4. Establish and monitor Department-wide energy metrics.

The Energy Security Strategic Plan is awaiting signature and will be released shortly. The Services also have established strategic plans and organizational structures to coordinate energy.

DoD is making progress in energy. Since 2006, DoD has more than doubled its energy investment, from $440 million to over $1.3 billion in FY 2009, not including energy-related funding in the Recovery Act. Overall energy consumption is down six percent since FY 2005. Installations energy demand is down 10% since FY 2003, and 12% of our electricity comes from renewable sources.

We have also initiated numerous demonstrations and other projects, aligned with the strategic plan, with anticipated savings from five to 25%, and successful technologies are being implemented on a wider scale. For example, the Army's demonstration for insulating tents resulted in an energy savings of 30 to 60% and was expanded to units in Iraq and Afghanistan. Other demonstrations will impact technologies to be integrated in acquisition programs, like the next generation of ground vehicles for which fuel efficient technologies are being tested. We are also changing our business processes to value energy appropriately and to articulate the return on investment, both financially and in terms of operational capability.

These efforts will improve the Department's energy posture by reducing costs and enabling sustained, uninterrupted operations. Efforts at tactical installations may also reduce the number of vulnerable fuel convoys, thus putting fewer Soldiers, Sailors, Airmen and Marines in harm's way. There's still much work to do, but the DoD is on the right path.

Mr. Alan Shaffer
Executive Director,
DoD Energy Security Task Force

This special issue on power and energy is the result of a collaborative effort between AMMTIAC and WSTIAC. In addition to all the authors who contributed, I extend my deepest appreciation to the following individuals whose efforts were intrgral to this publication. Mr. Terry Heston, Ms. Glenda Smith, Dr. Khershed Cooper, Mr. David Erpelding, Mr. Mike Morgan, Mr. John Weed, Mr. Christian Grethlein, Mr. Stephen Ashford, Ms. Mary Priore, Ms. Cynthia Long, Ms. Tamara Grossman, Ms. Perry Onderdonk, Mr. Brett Ingold, Mr. Owen Conniff, Mr. Christopher Fink, Mr. Richard Lane, Ms. Caron Dibert, and Ms. Judy Tallarino.

Ben Craig, Editor-in-Chief

The *AMMTIAC Quarterly* is published by the Advanced Materials, Manufacturing, and Testing Information Analysis Center (AMMTIAC). The *WSTIAC Quarterly* is published by the Weapon Systems Technology Information Analysis Center (WSTIAC). AMMTIAC and WSTIAC are Department of Defense (DoD)-sponsored Information Analysis Centers (IACs), administratively managed by the Defense Technical Information Center (DTIC). Policy oversight is provided by the Office of the Secretary of Defense, Director of Defense Research and Engineering (DDR&E).

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Issue Focus:
New Power & Energy Technologies for the Warfighter

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Department of Defense Energy Security Initiatives

Prepared by the DoD Energy Security Task Force
Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics)

INTRODUCTION

Energy is a strategic resource that has significant security, economic, geo-strategic and environmental implications for the nation and important operational implications for the Department of Defense (DoD). The focus of the DoD, like much of the nation, is to reduce demand through culture change and increased efficiency. The DoD is undertaking numerous initiatives and activities to promote energy savings and energy efficiency across the Department. This article presents an overview of some of these efforts.

> "We will always field the finest fighting force in the world ... but that force is extraordinarily energy dependent ... and unfortunately, we may be learning the wrong lessons in the Middle East where fuel is readily available. We need alternative solutions."
> Former Deputy Secretary of Defense, Gordon England

ENERGY IS A LIMITING FACTOR

The intensity of day-to-day fuel demand in Iraq and Afghanistan is greater than in any war in history. In fiscal year (FY) 2007, The DoD's total energy costs exceeded $13 billion, and an additional $5 billion was requested in FY 2008 to cover increased fuel costs.

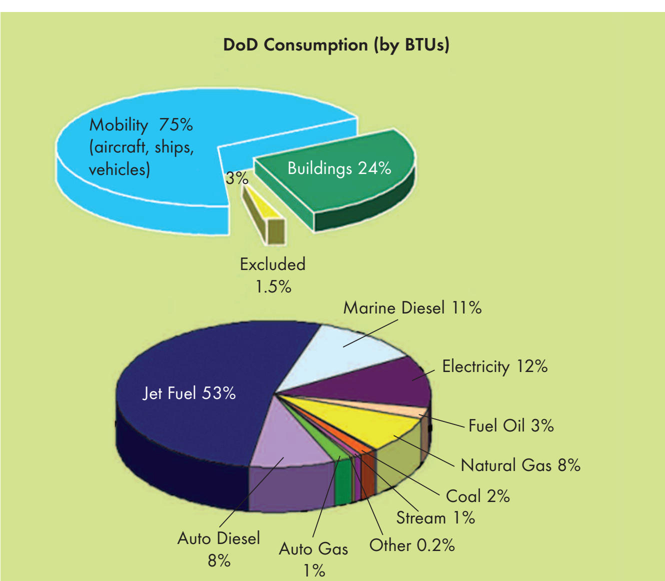

Figure 1. DoD FY07 energy consumption.

Figure 1 shows a breakdown of DoD energy consumption in FY07. Logistics convoys along vulnerable lines of communication are prime targets for insurgent forces. Protecting these convoys imposes a high burden on combat forces by diverting combat units from direct engagement to force protection missions. The strategic importance of energy security is well appreciated by decision-makers. However, energy is also tactically relevant as exemplified during Operations Iraqi Freedom and Enduring Freedom, and field commanders are looking to the Department and Services to provide battlefield solutions that reduce vulnerability while increasing capability.

From a tactical or operational perspective, reducing fuel demand can remove convoys from the battlespace, reduce operational vulnerability, and free combat forces for other missions. More efficient combat and combat-related systems inherently have greater endurance, extending the battlespace by enabling forces to travel longer distances and remain concealed longer without refueling. From the Departmental force planning perspective, greater energy efficiency in the force provides the option of either reducing the size of the fuel logistics force structure (move people and investment from the "tail" to the "tooth"), or maintaining more reserve logistics capacity to reduce future operational risks. Finally, greater fuel efficiency in the force reduces direct operating costs, mitigating the budget effects caused by commodity price volatility.

Fully Burdened Cost of Fuel

In 2001, a Defense Science Board (DSB) task force estimated the minimum cost of delivering over-land fuel in a combat zone to be $15 per gallon without including force protection, and the cost of delivering a gallon of fuel through an airborne tanker at $26 (excluding the cost of buying the aircraft). These estimates were based on a commodity price at the time of less than ninety cents per gallon for fuel. In 2006, the JASON* Defense advisory group estimated the cost of delivering a gallon of fuel via an airborne tanker, including a small proportion of the cost of the aircraft, at approximately $42 per gallon. The term coined to capture this more realistic cost of delivered fuel in theater is *fully burdened cost of fuel* (FBCF). The FBCF (vice fuel-only costs) will be used as part of the cost analysis conducted for new acquisition programs, as well as in retrofit, reconstitution, or upgrades that are being considered. Efforts are currently underway to more accurately quantify FBCF for various types of systems in a range of appropriate scenarios. This will support both smarter force planning and technology development investment.

Defense Energy Security Task Force

In May 2006, the Secretary of Defense commissioned the Director, Defense Research and Engineering to chair the Energy Security Task Force (ESTF) to define an actionable investment roadmap for lowering DoD's fossil fuel requirements and developing alternate fuels for use by the Department. The ESTF is comprised of senior leaders from across the Department with a stake in energy, including: requirements development, technology, acquisition, logistics, installations and environment, policy, and the budget. By taking a systems approach, integrating different functional areas, the indirect and potentially negative unintended consequences of various courses of action can be better understood, thereby improving decision making for the Department.

Underscoring the importance of energy to the Department, the Secretary of Defense designated Energy Initiatives as one of the Department's Top 25 Transformational Priorities, and the military departments have established energy leads and task forces, responsible for overseeing all energy efforts. The DoD is currently working to better understand the value of energy in terms of cost and operational capability, and to modify business processes to more accurately integrate those values into decisions that affect requirements planning, acquisition and funding priorities.

ENERGY SECURITY INITIATIVES AND ACCOMPLISHMENTS

The DoD is actively focused on initiatives to reduce energy demand, increase alternative sources of energy, and ensure the energy is delivered reliably and efficiently. Although the DoD's emphasis is on addressing energy security, many of these initiatives may also benefit the environment through increased production of renewable energy, improved use of resources and disposal of waste products, and reduced greenhouse gas emissions.

DoD Energy Security Strategic Plan

To provide a coherent direction across the spectrum of energy issues, the ESTF is finalizing a DoD-wide Energy Security Strategic Plan to address the issues and focus the myriad energy organizations that control and are impacted by energy variables. The plan will establish actionable policies, practices and metrics, and will require accountability to secure enterprise-wide buy-in.

The ESTF assessed energy consumption of platforms and facilities, identified the largest energy users, and developed an overarching strategy that addresses six functional areas:

- Fuel Optimization for Mobility Platforms
- Operational Efficiencies/Optimization and Commercial Practices
- Facility Energy Initiatives
- Domestic Energy Supply and Distribution
- Tactical Power Systems and Generators
- Geopolitical Considerations

The Energy Security Strategic Plan lays out four higher level goals that cut across these functional areas and describe a desired future state for the Department with respect to energy.

1. Reduce Demand
2. Assure Supply
3. Improve Processes
4. Establish and Monitor Energy Metrics

Goal 1: Reduce Demand

In order to enhance mission effectiveness, the systemic demand for fuel from DoD platforms, weapons, and fixed and tactical installations must be reduced. The DoD is exploring and implementing technologies that would reduce energy consumption. The installations community has made significant progress in reducing energy consumption (over 30% since 1985). In FY 2007, the Department reduced energy usage by over 10% from the 2003 baseline and has a mandate to continue reducing consumption by three percent per year through 2015. This will be accomplished through a variety of technologies such as sustainable design, which will reduce life cycle costs. For platforms, efforts cover a variety of technical areas, including lightweight materials and armor, novel structural shapes and more efficient powerplants (engines, motors, power storage, etc.), to identify ways to reduce fuel consumption affordably and sustainably, while sustaining (or enhancing) operational capability.

Facilities

The DoD established an Executive Committee, led by the Deputy Under Secretary of Defense for Installations and Environment, to address the goals set forth in recent federal energy guidance, including the Energy Policy Act of 2005, Executive Order 13423: "Strengthening Federal Environmental, Energy, and Transportation Management" and the Energy Independence and Security Act of 2007. The Executive Committee is coordinating and prioritizing these initiatives and is serving as a conduit to the Energy Security Task Force for installation and environmental energy issues.

Net-Zero Plus Initiative at the National Training Center (NTC), Fort Irwin, California. NTC is currently exploring the feasibility of removing their facilities completely from the electric grid and could have the potential to sell "green" energy back to the California grid. The Army has named Fort Irwin as a Net-Zero Plus Installation.

Efficient technologies for housing demonstration, Fort Belvoir, Virginia. The Power Surety Task Force and the Army's Rapid Equipping Force are demonstrating spray foam insulation (see Figure 2) and a solar power and storage system in Fort Belvoir housing. The Fort Belvoir demonstration includes a "control" case (with no new energy technologies) and will test the effectiveness of several technologies in three additional houses, each with successively more energy technologies. This $115,000 demonstration will provide data to determine the most cost effective combination of insulation and solar cells.

Pentagon Wedge 5 Renovation.† The Pentagon Renovations office has approved the use of LED light fixtures in place of the fluorescent and other lights used in the previous renovated

Figure 2. **Installing foam insulation on houses at Ft. Belvoir.**

wedges. The effort involves 4,200 light fixtures, each of which uses approximately 20 W less energy, yielding a total energy savings of 376,000 kWh/year (i.e., for one-fifth of the Pentagon). The fixtures are expected to last about 11.5 years, resulting in a net savings of about $4 million over the life of the fixtures.

Platforms

Fuel efficiency for turbine engines. The Highly Efficient Embedded Turbine Engine (HEETE) initiative, part of the Versatile Affordable Advanced Turbine Engine (VAATE) program, is developing high-pressure ratio, high temperature core technology, with the potential to reduce specific fuel consumption up to 25% over current systems. HEETE is addressing the highest technical risk element in new engine development – the high pressure compressor component development. The current schedule includes a rig test in FY 2010, demonstrating a technology readiness level of four or five in a laboratory or relevant environment. These technologies are applicable to all turbine engines and could be used in commercial aircraft.

Efficient engines for Unmanned Aerial Vehicles (UAVs) and generators. The Small Heavy Fueled Engine demonstration is a three year program, initiated in FY 2008, and is anticipated to increase fuel efficiency and power density by 20% for UAVs and generators. The three engines assessed in the demonstration will operate on heavy fuels such as JP-8, thereby reducing the number of different fuels used on the battlefield and reducing the strain on the logistics tail.

Testing fuel efficient equipment on ground vehicles. The Fuel Efficient Demonstrator (FED) is testing the feasibility and affordability of achieving significant decreases in fuel consumption in a tactical vehicle, without sacrificing the performance or capability. This program is integrating potentially high-payoff fuel efficient technologies, like efficient propulsion and drivelines, and advanced lightweight materials in new and innovative designs. Successful technologies may be incorporated in future procurements for the Joint Light Tactical Vehicle (JLTV).

Diesel hybrid vehicle testing. The Department is testing various diesel hybrid vehicles (see Figure 3). Hickam Air Force base is testing a plug-in parallel hybrid drive system to be integrated into a step van that will provide improved efficiency, superior performance and greater fuel economy. The system design consists of a 2.5 liter/75 kilowatt (kW) diesel engine, a 97 kW AC induction motor, and a continuous variable transmission. The Air Force is also testing and demonstrating Heavy Duty Hybrid Electric Class 8 Mack Trucks, with an Integrated Starter Alternator Motor which assists the diesel engine to provide power to the drive train. The trucks are being used by the Civil Engineering and Aircraft Refueling activities.

Extended range UAVs. The Air Force completed a preliminary design review for a prototype long endurance UAV to fly medium altitude missions un-refueled for five to seven days. The intent of this demonstration was to provide for affordable persistent surveillance using the latest energy efficient aviation technologies. Although the preliminary design review found the budget was insufficient to build and demonstrate a flying prototype, insights from this program may be integrated into other ongoing UAV programs, including the Army's Orion program.

To provide extended intelligence, surveillance and reconnaissance mission capability, the Naval Research Laboratory (NRL) is developing a fuel cell powered UAV with a projected endurance exceeding 24 hours operation on hydrogen gas. The UAV and fuel cell are being designed as an integrated package, and the project is planned for completion in 2009.

Figure 3. **Diesel hybrid vehicle testing at Hickam AFB.**

There are also two Joint Capability Technology Demonstration (JCTD) programs investigating even longer flight times. The Global Observer JCTD will demonstrate a liquid hydrogen powered unmanned aerial vehicle, using a modified, off-the-shelf internal combustion engine, capable of flying extremely long endurance, up to 7 days, with a moderately sized payload capacity at an altitude of 55-65,000 ft. The Zephyr JCTD will demonstrate and transition into service a solar-powered unmanned aerial vehicle capable of flying continuous operations for months at a time using solar power plus batteries for continual day/night operations.

Operational Efficiencies

The ESTF is working with the Combatant Commanders to understand their energy needs and concerns, which vary in priority among the different commands. For example, Central Command is primarily concerned with the dangers of inefficient fuel movement to forward operating bases, while the European Command is focused on the security aspects associated with energy suppliers using energy as a way to exert influence over other nations. The newly formed Africa Command is looking for sustainable energy capabilities for security cooperation to enable power generation or fuel generation in remote and/or austere environments.

The Power Surety Task Force (PSTF), formerly part of the Army's Rapid Equipping Force (REF), has been transferred to the ESTF, and one of their primary roles is to serve as a liaison with the Combatant Commanders and provide support for energy considerations. The PSTF has tested a variety of new energy technologies that can be used in theater. Their process of first reducing demand, then conducting an engineering assessment to remove wasteful generation or excess capacity, and finally, supplementing with alternative and renewable energy, will enable forward bases and other installations to set the foundation for optimizing energy use in the long-term.

In an effort to demonstrate the operational efficacy of demand reduction coupled with alternative/renewable power, the PSTF and the NTC installed energy efficient structures (domes, sprayfoam insulation, renewable power generator, and efficient heat-

Figure 4. Monolithic dome and renewable energy generator at NTC.

ing, ventilating, and air conditioning systems) in the training area (see Figure 4). These structures demonstrate a holistic approach that can provide an estimated energy savings of about 60%. This proof of concept effort was intended to make forward operating bases energy independent for power generation.

In July 2007, the PSTF and REF demonstrated a technique for insulating temporary structures, such as tents and containerized living units, using an exterior application of spray foam. The resulting energy savings of 40-75% led Multi-National Force Iraq to award a $95 million contract to insulate nine million square feet of temporary structures. Based on extrapolated data from previous demonstrations, the additional nine million square feet of insulated temporary structures could save more than 77,000 gallons of fuel per day in theater, equivalent to about 13 truckloads of fuel, with associated cost savings of over $300,000 per day at $4 per gallon (not including the military logistics and force protection saved from the demand reduction).

Increased use of simulators for training. Preliminary studies have indicated that the increased use of simulators could potentially yield significant savings, resulting from reduced fuel costs, maintenance, and platform "wear & tear". The Joint Staff is leading a study to assess current simulator usage, develop a cost model for the business case supporting greater simulator use, and determine the feasibility of substituting additional simulator time for live training without decreasing operational capability.

Goal 2: Assure Supply

The DoD must minimize risk in energy availability, accessibility and distribution to military operations while sustaining operational capability. In addition to improving combat unit capability (by reducing dependence on its fuel tail), some technical solutions for reducing platform fuel demand show promise for increasing individual capability as well. The DoD is shifting reliance toward alternative and renewable sources of energy, thereby reducing dependence on non-assured sources of oil.

Renewable Energy

In FY 2007, the DoD reduced energy usage by over 10% from the 2003 baseline and almost 12% of the electricity was generated from renewable energy sources. The DoD is increasing use of "traditional" renewable energy sources (e.g., solar, wind, etc.) and is also exploring new technologies, such as ocean and wave harvesting.

Figure 5. Nellis Air Force Base solar array.

Solar power. Solar power is the largest contributor in the Air Force's renewable energy development program. In December 2007, the Air Force commissioned the largest photovoltaic solar array in the Americas (14.2 megawatts) at Nellis Air Force Base (see Figure 5). This supports about one fourth of the base's energy usage per day and has an estimated annual cost savings of $1 million. In 2007, the Air Force continued to lead the federal government in green power purchases, with 37 bases meeting some portion of their base-wide electrical requirements from commercial sources of wind, solar, geothermal, or biomass. Additional solar projects on underutilized land are planned using the enhanced used lease authority.

Geothermal power. The Navy has made good use of the authority in 10 U.S.C. 2922a to receive revenues from geothermal power facilities, as they have done with the development of the 270 megawatt plant at China Lake, California in the 1980s that provides enough power to supply electricity to 180,000 homes. The Navy recently awarded a contract to build a 30+ megawatt geothermal plant at Fallon Naval Air Station, Nevada, and the Department is looking at other opportunities for similar public/private ventures. The Department is exploring the feasibility of expanding the Title 10 authority to enable DoD to receive revenue from other energy resources on its lands. Ground source heat pumps are increasingly being used, particularly at housing units. For example, Offutt AFB has installed 1,131 tons of ground source heat pumps for its dorms.

Testing other potential energy generation technologies. The Navy is testing other energy sources for their feasibility to produce energy cost effectively. The Navy installed the first wave power buoy at Marine Corps Base Kaneohe Bay, Hawaii, and is partnering with industry to test a second buoy. In addition, the Navy is contracting with a commercial firm to provide a technology demonstration of tidal energy harvesting in the Puget Sound area. The Navy also is partnering with the British Government to design and install a barge mounted off-shore Ocean Thermal Energy Conversion (OTEC) plant for electrical and water requirements at Diego Garcia.

Solar roofs. Thin-film solar panels are being used increasingly by the Department. Naval Base Ventura County installed an 87 kW rooftop amorphous silicon thin-film photovoltaic (PV) laminate system on a building in Port Hueneme, California, and the Navy also installed photovoltaic parking garages at Naval Base Coronado (see Figure 6), North Island, California, producing one megawatt of power. The Defense Commissary Agency initiated installation of a roof mounted, PV array capable of producing an estimated 152 kW at the Los Angeles AFB Commissary in California.

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Figure 6. **Photovoltaic parking garage at Naval Base Coronado, North Island, California.**

Alternative Fuels/Energy Sources

The Department is pursuing a variety of efforts in alternative fuels, primarily focused on testing and certification, enabling our systems to use different fuels regardless of the feedstock or production method. We already rely on local fuel sources in theater, like Jet A-1 (commercial jet fuel) in Europe, which differs slightly from JP-8. Efforts include improving the combustion process of engines using alternative fuels, optimizing fuel composition, understanding the equipment and systems impacts of alternative fuel use, such as corrosion and wear, and establishing protocols for alternative fuels qualification in aircraft, ships, vehicles and generators.

Synthetic fuel (synfuel) certification. Several efforts by the Services are underway to test and certify synfuels on both aircraft, ground vehicles, and support equipment. For example, in August 2007, the Air Force certified the B-52 to use a 50/50 blend of synthetic fuel and conventional aviation fuel. They have since certified the B-1 and C-17 (see Figure 7). Tests are underway to certify the F-15 and F-22 in the near future, with an objective to certify the entire Air Force fleet by early 2011. The Air Force has a goal to cost-effectively acquire 50% of its continental US aviation fuel via a synthetic fuel blend utilizing domestic feedstocks and produced in the US by 2016, with the intent to require that the synthetic fuel purchases be sourced from suppliers with manufacturing facilities that engage in carbon dioxide capture and effective reuse resulting in the use of fuels that have a "greener" life cycle environmental foot print the petroleum-derived products.

Figure 7. **C-17 transcontinental flight using a synfuel blend.**

The Air Force is developing an Assured Aerospace Fuels Research Facility to support the study and evaluation of how processing and upgrading operations, conditions, and catalysts impacts the production, characteristics, quality, and carbon dioxide (CO_2) footprint of jet fuel made from alternative sources. Joint studies sponsored by the Air Force and the Department of Energy (DOE) show potential life cycle CO_2 reductions below that of conventional petroleum if waste biomass is combined with coal to produce aviation fuels via Fischer-Tropsch (FT) processing. This facility will enable the Air Force to conduct a comprehensive analysis of the potential that biomass may offer to reduce the life cycle CO_2 footprint of FT technology. Looking beyond FT fuels, the Air Force, in partnership with DARPA and industry, is investigating the suitability of second and third generation biomass-derived transportation fuels (e.g., cellulosic biomass, algae oils, animal fats, etc.) as renewable feedstock options for aviation use.

The Navy is conducting research on the effective use of alternative logistics fuels in naval power systems. These efforts include addressing the impacts these fuels have on engine internals and fuel distribution system components, optimizing fuel composition and improving the combustion process. The Navy also is establishing protocols for alternative fuel qualification for use on naval vessels and aircraft. In addition, the Army is testing a wide range of alternative fuels at the Army Research, Design, and Engineering Command in Warren, Michigan.

The Services and the Defense Energy Support Center are also working closely with the Commercial Aviation Alternative Fuels Initiative that represents the airlines, airports, and manufacturers to efficiently and economically certify the commercial airline fleet. This effort builds on the fact that many aircraft in the commercial and military fleets share common platforms, systems and engines.

Investment in biofuels. Commercially available biofuels are in limited supply and have lower energy density than their petroleum-based equivalent. Research suggests that some bio-based feedstocks could be converted into hydrocarbon fuels efficiently and affordably. Since the military's primary fuel source is jet fuel, DARPA is demonstrating the ability for oil rich crops, such as algae, cuphea and jatropha, to create JP-8 at energy density levels sufficient to power military systems.

Carbon capture and reuse. In FY 2007, the Air Force and the Office of the Secretary of Defense collaborated with the Department of Energy's National Energy Technology Laboratory (NETL) and Arizona Public Service in a program to develop a method to use algae to reuse CO_2. The work involves development of an algae-based CO_2 absorption system which produces algae oils that can be further developed into jet fuel. The Air Force helped develop the establishment of a laboratory at Arizona Public Service to study this algae oil-to-jet fuel process.

Biodiesel life extension program (O28 O2Diesel™). Military vehicles can experience mechanical problems when using standard biodiesel, as stagnant biodiesel develops microbial growth leading to contamination and degradation. The Air Force is completing a $5 million demonstration with an ethanol/bio-diesel fuel blend (7% ethanol/20% pure biodiesel), with tests conducted on numerous vehicles in a variety of different climates. The new blend (O28 O2Diesel™)‡ eliminates and prevents the contamination while reducing particulate matter emissions by up to 80%. In addition, the Navy is constructing a biodiesel production facility to further prove the feasibility of using cooking oil to produce fuel.

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Hydrogen technology testing. The Air Force Advanced Power Technology Office (APTO) is conducting hydrogen technology and capability demonstrations at Hickam AFB. (This effort is described in the article by Thomas Quinn in this issue.)

The Navy is continuing a hydrogen fuel station and non-tactical fuel cell vehicle (FCV) demonstration at Camp Pendleton Marine Corps Base, California. This effort is an Environmental Security Technology Certification Program (ESTCP) project to demonstrate and validate an on-site steam methane reformer for hydrogen production. The project successfully completed demonstrations with a General Motors (GM) hydrogen fuel cell pick-up truck and sports utility vehicle in FYs 2006 and 2007, and will lease three GM FCVs to demonstrate extended vehicle range capability and to provide fuel cell test data in support of potential naval electric ship applications.

Waste-to–energy systems. The Air Force APTO is working to integrate a waste-to-energy system at Eielson Air Force Base, Alaska (see Figure 8). This system will be an advanced gasification-based core technology with the capacity to convert 10 to 50 tons per day of a wide variety of waste materials into 1 megawatt of clean electricity, to be used on-site by the base, thereby reducing the amount of electricity purchased from the local grid. This will reduce energy costs and improve the security of the base, enabling the base to use onsite sources to produce renewable energy, independent of the local grid. In a rapid-deployment scenario, the technology can help the Air Force reduce the use of imported fuels at installations in the short term. Waste-to-energy systems provide a tool for achieving both the renewable energy and landfill avoidance goals established by Executive Order 13423.

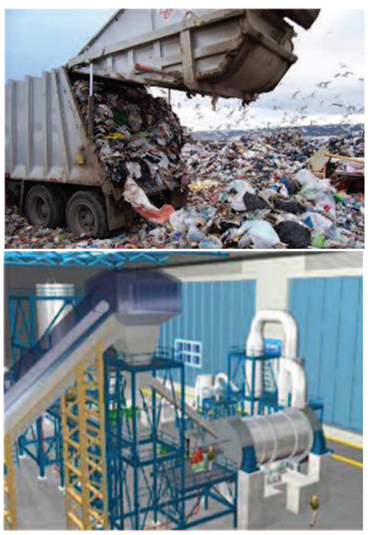

Figure 8. **Waste to energy technologies, Eielson, AFB.**

Very high efficiency solar cells. DARPA demonstrated breakthrough conversion efficiency with a set of solar cells (over 42%) and is currently using this set in a proof-of-concept solar power module with an objective of 40% efficiency, which would be almost double that of current solar power modules. The end-of-program goal is to achieve 50% efficiency affordably at the module level. The DARPA module is using a novel lateral cell design that will be optimized in spectrally split band gaps (high, medium-high and low). If successful, this could be a game changer, making solar energy cost effective.

Nuclear Energy Initiative. The Air Force was asked by several members of the US Senate to determine if Air Force bases could be appropriate siting locations for small package nuclear power generation facilities. The Air Force issued a request for information (RFI) to gauge industry's interest in the concept, and to solicit their ideas on potential technologies, financing options, and other aspects of a potential project. The Air Force model is for this completely commercially driven. The Air Force will not build, own, operate, or license a nuclear power plant. The goal is to provide a suitable site, and as a customer and market leader, provide the opportunity for the private sector to build and operate the plant, using an enhanced use lease (EUL), or similar, authority.

Tactical Power Systems and Generators

Transportable Hybrid Electric Power Stations (THEPS). The REF completed testing of Transportable Hybrid Electric Power Stations. These devices were requested by Major General Zilmer, Operational Commander in the Al-Anbar province in Iraq, in response to the vulnerability of US Forces while delivering fuel. Although significant fuel savings were found, the systems were not robust enough for a forward operating base environment. However, insights from this effort were used to advance the Hybrid Intelligent Power program.

Hybrid Intelligent Power (HI-Power) generator. The HI-Power program is a revolutionary effort that will develop and validate a DoD standard tactical intelligent power management architecture (see Figure 9) that incorporates source management (including the use of renewable energy sources where applicable), energy storage technologies, power distribution, and demand management.

Solutions currently being pursued include the development of active distribution networks and intelligent, automated hybrid power systems. Power management and distribution techniques will enable maximum power utilization with a high degree of efficiency for use with various mobile and portable applications in the 2 to 500 kW range.

Figure 9. **Hi-Power generator at Ft. Belvoir, VA.**

This power management architecture will include small and medium sized tactical versions for mobile forces and larger transportable systems appropriate for forward operating bases. Initial models estimate fuel savings of up to 40% compared to current systems, reduced maintenance and personnel requirements, and fewer power interruptions. The resulting architecture will impose minimum impacts on transportability, deployability, and readiness levels of current and upcoming platforms.

Tactical Garbage to Energy Refinery (TGER). The REF has deployed two TGERs to Iraq for a capability demonstration and evaluation. TGER, shown in Figure 10, converts field waste (paper, plastic, cardboard and food slop) into biofuel that is used to power a 60 kW generator. A battalion sized forward operating base (600-800 soldiers) creates about one ton of garbage per day that can be recycled into energy, so the system is designed to convert one ton of waste into energy equal to about 100 gallons of JP-8. It is skid mounted and deployable on a military 5-ton flatbed trailer.

Figure 10. Tactical Garbage to Energy Refinery (TGER).

Solid Oxide Fuel Cells. The Navy and Army are developing and demonstrating compact and mobile 10 kW high-temperature fuel cells to power critical equipment, including GPS, radio and communications equipment, computers, intelligence, surveillance and reconnaissance gear, and laser designators. These systems provide silent, portable power and eliminate dependence on large generator or grid power for battery charging. These fuel cells are demonstrating a high efficiency (approximately 55%) and are being designed to be compatible with kerosene-based jet fuels such as JP-5 and JP-8. They provide low weight for the available energy content to the warfighter carrying them. Additionally, they will provide auxiliary power for applications on vehicles for missions over 24 hours.

Remote Site Tactical Hybrid Power. The 3rd Brigade, 1st Armored Division in Iraq, used excess electricity generated from his Forward Operating Base (Camp Taji) to provide power to the local Iraqi population as part of his engagement strategy to facilitate better community relations. This resulted in enhanced security for local population, enhanced security for coalition forces and created a safe and secure environment through a more cooperative relationship with the local population.

Expanding on this success, the REF has selected a vendor to deploy a hybrid generator (wind, solar, battery storage, back-up diesel) for US Forces at a Kuwaiti border crossing communications site, based on an assessment by the Power Surety Task Force. The intent of this effort is to demonstrate the efficacy of commercial hybrid power stations in meeting military needs in isolated, but fixed locations.

Goal 3: Improve Processes

Properly valuing energy in acquisition decisions will aid in reducing life-cycle operation and sustainment costs, thereby dampening price fluctuation impacts on the Department. Opportunities to leverage efforts by other organizations, such as federal agencies, industry, academia, and the international community, are also being identified. In addition, the DoD is evaluating the strategic and operational implications of global energy economics and associated security issues, including where a global energy supplier has the ability to exert influence over its consumers. The Department also wants to retain its role as a good environmental steward, remaining cognizant of potential environmental impacts and how our actions may be perceived in the globally. The Department has made progress to incorporate energy considerations in its planning and business processes.

Requirements Generation and Acquisition

Energy in the requirements development process. In August 2006, the Vice Chairman of the Joint Chiefs of Staff signed a memorandum establishing the requirement for an energy-related Key Performance Parameter (KPP) for new acquisition programs to be selectively applied. KPPs are attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability. The methodology and procedures for establishing program-relevant energy KPPs are under development. In May 2007, the Joint Staff updated their directives§ to require use of KPPs as established in the Vice Chairman's memo. The energy efficiency KPP requires life-cycle cost analysis to include the burdened cost of fuel in the Analysis of Alternatives (AoA) and/or Evaluation of Alternatives (EoA) and subsequent analyses and acquisition program design trades. In such analyses, the fully burdened cost of fuel is defined as the price of the fuel, plus its delivery chain and force protection requirements, all taken from a range of the applicable defense planning scenarios. This scenario-based force planning methodology will underpin both the KPP within the DoD requirements process (Joint Capabilities Integration and Development Process (JCIDS)) and the calculation of the fully burdened cost of fuel in acquisition.

Energy in the acquisition process. The acquisition process is currently under revision to more accurately value energy. In April 2007, the Under Secretary of Defense (Acquisition, Technology and Logistics) signed a policy memorandum to use the fully burdened cost of fuel as a major basis for all trade analyses for acquisition programs. The memo also established three pilot programs (the Joint Light Tactical Vehicle (JLTV), alternative ship propulsion for the next generation cruiser (CG(X)) and the Next Generation Long Range Strike (Next Generation Bomber)) to validate the approach and to facilitate development of policies and procedures for how to apply it in the acquisition process. In December 2008, the DoD acquisition directive (5000.2) directed energy costs be included in calculations for total ownership costs, to include the fully burdened cost of fuel.

Fuel logistics considerations in wargames. The Services have begun to incorporate additional energy considerations in periodic force planning wargames. These exercises will provide a better understanding of the impact of energy on operations in the mid- to long-term and will help the requirements and acquisition communities to evaluate the operational value of raising energy efficiency requirements of new systems and for refurbishment of legacy systems.

Partnering

The Department is actively seeking opportunities to partner with other federal agencies, industry, academia and the international community to leverage their ongoing efforts in energy. A number of DoD components are working with the Combatant Commanders and the Power Surety Task Force to assess and resolve their energy needs. The DoD is also collaborating with foreign governments to identify areas of commonality to leverage cooperative efforts.

A small portion of Energy Conservation Improvement Program (ECIP) funding is being used to leverage ESTCP funding on facilities energy technologies. In FY 2007, these programs combined to fund four projects: a building integrated photovoltaic roof, innovative fast pyrolysis technology, liquid-desiccant outdoor air conditioning, and a micro-turbine power generator. In each of these projects, ECIP funds the construction, and ESTCP funds the monitoring and validation. Technologies that are proven through this process can then be spread throughout the DoD.

Goal 4: Establish Metrics

The final goal focuses on measuring the Department's progress by establishing performance targets and metrics based on quantifiable analysis. These performance measures will help to increase awareness and visibility of energy issues; incentivize, measure and reward progress; and change the Department's culture to value energy appropriately. Collectively, these goals establish the framework for managing energy across the Department.

The installations and environment community has a well-defined series of metrics to monitor energy consumption and the use of alternatives, as outlined in annual reports and scorecards. Examples are included in the sidebar below. The DoD is in the initial stages of considering how to adapt this for platforms.

SUMMARY

The Department has a balanced portfolio of energy efforts in place, either in testing or in the planning stages. Our business and planning processes are being amended to better determine the value of how and how much to reduce energy-related risks, while maintaining or improving capabilities. The Department is developing and testing technologies to manage supply and demand more effectively. The DoD Energy Security Strategic Plan will provide senior leaders with a clear, forward-leaning, and operationally-focused set of options to deliver a much more sustainable, resilient force with greater endurance over the full range of future missions. The Department's strategy recognizes the value of energy and puts us on a path to greater energy security.

NOTES

* JASON is an independent advisory body of highly accomplished scientists and other scholars who self-select endemic issues and challenges facing the Department and attempt to provide actionable solutions.

† Additional examples and details can be found in the Annual Energy Management Report (http://www.acq.osd.mil/ie/irm/Energy/energymgmt_report/fy07/DoD-Narrative-Final.pdf).

‡ O28 is a renewable-based biodiesel formulation consisting of O2Diesel™ and B20 biofuel.

§ Chairman of the Joint Chiefs of Staff Instruction (CJCSI) 3170.01F - Joint Capabilities Integration and Development System (JCIDS) and Chairman of the Joint Chiefs of Staff Manual (CJCSM) 3170.01C Operation of the Joint Capabilities Integration and Development System (JCIDS).

Energy Goals

- Reduce fuel demand → implies annual reduction [National Defense Strategy June 2008]
- Reduce installations energy usage by 30% by 2015 [Executive Order (EO) 13423 / 2007 Energy Act]
- Reduce petroleum consumption for non-tactical vehicles by 20% by FY15 [2007 Energy Act]
- Certify synfuel in all Air Force aircraft by 2011 [Secretary of the Air Force goal]
- 25% of electricity from renewable sources by 2025 [National Defense Authorization Act 2007]
- Reduce fossil fuels in new/renovated buildings: 55% by 2010; 100% by 2030 [2007 Energy Act]
- 30% of hot water in new/renovated buildings from solar by 2015 [2007 Energy Act]
- Increase non-petroleum fuel by 10% per year [EO 13423/2007 Energy Act]
- Energy as selective Key Performance Parameter [Chairman, Joint Chiefs of Staff Instruction 3170.01F/Chairman, Joint Chiefs of Staff Manual 3170.01C]
- Fully burdened cost of energy in tradeoff analyses [USD(AT&L) memo of April 07]
- Energy included in life cycle sustainment metrics for MDAPs [USD(AT&L) memo of July 08]
- Building metering data entered into benchmarking database [2007 Energy Act]
- Electricity metering by October 2012 [2005 Energy Act]
- Natural gas and steam metering by October 2016 [2007 Energy Act]

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Lightweight Wearable Power Energized by Pentagon's Prize Program

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The format and general style of this article are somewhat of a departure from the standard articles we publish. Rather, it is more of a "conversation" with principals in the DoD engaged in the pursuit of lightweight wearable power technologies for the warfighter. We hope you'll find it as informative as we did! – Editor

The sophisticated electronic devices and sensors that give our dismounted warriors an edge on the battlefield also make them prodigious consumers of energy. Helmet-mounted displays, night-vision devices, image intensifiers, satellite radios, computers, laser range finders, global positioning systems, robots, and autonomous vehicles – all these technologies are straining the ability of ground combat personnel to carry adequate power sources to operate them. "Right now, one of the more significant limitations for our ground operations is available power," says Alan Shaffer, Acting Director of Defense Research and Engineering (DDR&E). "Assuming a warfighter has strength to carry a finite amount of weight, we want that weight to be as focused as much as possible on combat power." The question is how to supply enough power that is safe, long-lasting, and lightweight enough for soldiers, Marines, special forces, and Airmen on the ground to carry in a vest or pack along with their other provisions and equipment for extended ground missions. "The issue of wearable power is a very tough problem," says the Army Research Laboratory's (ARL) Senior Program Manager John Hopkins. "You don't necessarily see power on the battlefield. Because it's an enabling technology, and not an end item, it might not be the first problem you think of."

The demand for power will only grow as military technologies evolve, so the Department of Defense (DoD) decided to use its new prize authority, granted by the John Warner National Defense Authorization Act for Fiscal Year 2007, to solicit novel solutions for wearable power systems from the broadest possible population of inventors. By opening up this complex science and technology (S&T) challenge to nontraditional sources of innovation, the DoD sought not only to advance the concept of wearable power, but also to reach deeper into the well of American ingenuity and create public and academic interest in mission-critical problems facing the US warfighter.

"One of the more significant limitations for our ground operations is available power"

Wearable Power is a Weight Problem

The DoD estimates that a typical dismounted warrior on a four-day mission carries between 20 and 50 pounds of batteries and rechargers. Combined with the food, water, ammunition, and equipment needed for a multi-day mission, warfighters may have to carry as much as 150 pounds on their backs. "That's a lot of weight, and we are adding new electronic equipment to their loads all the time," Mr. Shaffer notes. The DoD estimates that, in 10 years, dismounted warriors will need about 50 watts of power per person to operate their equipment. Clearly, the systems used to deliver that power will have to get lighter. "In terms of weight, we were looking to decrease the soldier-carried power component of overall load from the 20 to 50 pound range to a range of less than 10 to 25 pounds. That makes a huge difference for ground combat personnel going out on long-duration missions," says Mr. Shaffer. "We knew we were seeking a tremendous advance in capability."

Wearable Power is a Logistical and Tactical Problem

The energy and power dilemma came to the forefront in the early days of Operation Iraqi Freedom, when an emergency program had to be instituted to replenish the supply of batteries available to forward operating forces. "The second largest demand for airlift at the time was for batteries," says Mr. Shaffer. US troops needed more battery power than had been planned to operate their equipment. Troops in the southern region used up more than half of the total projected battery supplies available in the first few days of the operation, draining forward stocks and bringing total Army inventory down to dangerously low levels. Troops in the northern region were unable to obtain batteries, which prompted the emergency airlift and triggered around-the-clock production of new inventories to catch up with warfighter demand.

Recognizing that DoD's investment in energy and power was not keeping up with battlefield technology, DDR&E created the Energy and Power Technology Initiative (EPTI) to marshal the full engagement of all the service branches to address these issues across the DoD. The EPTI, chaired by Acting DDR&E Alan Shaffer, brought together senior officials from the Office of the Secretary of Defense (OSD) and the research and development (R&D) organizations of the Army, Air Force, Navy, and Marine Corps. Through a series of technical directions, the EPTI is drawing what is essentially a technology roadmap that encompasses all the services and leverages and coordinates their combined research and engineering capabilities in energy and power.

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Attention Innovators: Calling All Ideas

After the DoD was accorded prize program authority in late 2006, the Hon. John J. Young, Jr., Undersecretary of Defense for Acquisition, Technology, and Logistics, asked the EPTI to propose an energy and power topic. "In light of the energy issues facing the country in general, and the fact that all three services faced similar challenges, this was clearly a high-priority issue," according to Dr. John Pellegrino, Director of Sensors and Electron Devices at ARL and the Army's Principal Representative to the EPTI. Deliberations identified a topic that was pertinent to all the services and would benefit from the participation of a broader community of innovators than those typically engaged in formal defense acquisition programs. Wearable power eventually rose to the top.

In 2007, DDR&E launched the Wearable Power Prize (WPP) program, the first-ever tri-service prize R&D competition. One million dollars was promised to the individual or team that could build a wearable power system that could produce, under realistic operational scenarios, an average of 20 watts of power for more than 4 days (96 hours) and weigh less than 4 kilograms (<8.8 pounds). The key metric for wearable power systems is *energy density* (a measure of available voltage per unit weight). As an additional hurdle, the systems were required to run two voltages (14 and 28 volts) simultaneously without a switch. This technical challenge recognized that different devices require different power draws, thus addressing a power management aspect of wearable power. For the second and third place entries, the WPP competition offered additional prizes of $500,000 and $250,000, respectively.

A total of 169 teams registered their prototypes in the competition. Among the initial registrants, self-identified individual private investors far exceeded the number of corporate-affiliated teams, an early outcome that supported one of the WPP's primary objectives. The entries ran the gamut from enhanced lithium-ion batteries to fuel cell/battery systems, engine/turbine and various other battery hybrids, and a plasma photon system. There were also a variety of fuel types and mixes, including everything from methanol and ethanol, to gasoline, propane, and butane. The competitors were just as diverse: teams hailed from 37 states and included members from several foreign countries. One team that made it all the way to the final competition consisted of two college students from the University of Maine. Other teams represented private companies or were cooperative groups consisting of university professors, students, and small entrepreneurs. Ultimately, 20 teams came to the capstone event, held from 22 September to 4 October 2008, at the Marine Corps Air Ground Combat Center at Twenty-nine Palms, California. A third of those teams were new to working with the DoD, another indication that the prize program was effectively drawing on nontraditional sources of ingenuity. By the time the winners of the "Power Wear Off" were announced on the last day of the competition, the WPP had brought forth prototype wearable power systems that represented the highest energy densities seen to date and more than a twofold decrease in conventional power system weight.

Why a Prize Program?

"The prize program format for solving a technical problem is a wonderful asset in our toolbox for building DoD's research and development portfolio," says Dr. Pellegrino. Prize challenges are employed by a number of public and private organizations to coax inventors to step forward with new approaches for solving stubborn technical problems. Prize programs are most fruitful "in areas where there is a general concentration of work and an overlap of interest with the private sector," according to Dr. Edward Shaffer, Associate Director in ARL's Sensors and Electron Devices Directorate. Prize programs can also function as "hooks for outliers such as university professors who may not be engaged with the defense research community through regular channels," adds Dr. Shaffer.

One such prize program was the Defense Advanced Research Projects Agency's Urban Challenge. The program offered prize money to developers of autonomous ground vehicles capable of maneuvering in a mock city environment and executing simulated military supply missions, while merging into moving traffic, navigating traffic circles, negotiating busy intersections, and avoiding obstacles. Another example is the Virgin Earth Challenge under which Richard Branson and Al Gore are offering a prize of $25 million to anyone who can demonstrate a commercially viable system for removing greenhouse gases from the atmosphere.

> "The prize program format for solving a technical problem is a wonderful asset in ... DoD's research and development portfolio"

A hallmark of a prize program is the likelihood of dual-use applications. In the WPP's case, this involves solutions that are not only relevant to defense and national security but also have potential for public sector or commercial uses. Wearable power has several dual-use applications. For example, outdoor recreation enthusiasts are interested in small, lightweight, power sources for camping, hiking, fishing, and mountain climbing. First responders, such as police and firefighters, also have technology that depends on a reliable source of lightweight power.

Wearable Power a Tri-Service Priority

From the start, DDR&E devoted senior-level talent to prize program planning and execution. Dr. William Rees, Under Secretary of Defense for Laboratories and Basic Sciences, assumed executive oversight, while execution responsibility was assigned to the ARL. Senior Program Manager John Hopkins was tapped as WPP Program Manager, and Karen Burrows was named Program Manager for DDR&E. Senior members of the EPTI formed the core executive committee for the WPP competition. They, in turn, pulled in the right subject matter experts (scientists and engineers from each of the service's R&D organizations) to serve on task-specific teams responsible for execution, safety evaluation, testing, and adjudication. "With respect to defining the criteria for the WPP challenge, the EPTI was well-suited to the task because of the relationships among S&T executives that were already well-established," says ARL's Dr. Ed Shaffer. These ties were instrumental in representing the needs and interests of dismounted ground combat personnel in all three service branches. "The predominant customer for wearable power is the soldier," notes Hopkins. However, by the nature of their jobs, Marines and other dismounted warfighters rely on stealth, sensory, and other advanced technologies in the performance of their critical missions. "We are very concerned about the weight that a Marine or Navy special forces fighter has to carry," says Dr. John Pazik, Director of Ship Systems and Engineering in the Office of Naval Research (ONR). These skilled warfighters are "not battery carriers," continues Pazik, "and we don't want to burden them with extra weight to power their devices. We want them to do their primary mission, get out safely, and return home. That's our primary goal."

"The Air Force has a strong stake with the other services in lightweight, energy-dense wearable power systems," asserts Dr. Richard T. Fingers, Chief of the Energy Power Thermal Division at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base. Airmen on the ground support the Air Force mission and work with other dismounted warfighters in theater to complete extremely complex missions. "In our special-purpose research area at AFRL, we have been investigating both wearable power and small unmanned aerial vehicles, which have similar lightweight power requirements," adds Dr. Fingers. "The prize competition was a true tri-service executed program," notes Air Force Major Derek Lincoln. Major Lincoln was among the military members of the core execution team who brought onboard the all-important user's perspective.

Let the Competition Begin!

After the initial WPP solicitation and a public information forum in September 2007, prospective competitors were given a month-long registration period to signal their intent to compete. To attract a diverse group of nontraditional competitors and remove perceived barriers to prospective entrants, anyone meeting the eligibility requirements could register. Team leaders had to be individual US citizens (although citizenship was not required for team members), at least 21 years old (age 18 for team members), and not currently employed by the federal government, either civilian or military. US and foreign-owned companies were permitted to enter, provided their team leader met the age and citizenship requirements, and state and local government organizations and public universities were also eligible. When registration ended on November 30, 2007, 169 teams had signed up to compete for the WPP purse. There were about ten months remaining before the final competition in the high desert of southern California's Mojave Desert.

Getting Down to Work

Setting the technical requirements for the WPP program was a balancing act. The prize criteria had to encourage broad inclusiveness and yet be challenging enough to yield meaningful advances in wearable power technology. "The criteria were the product of a great deal of interaction among technical experts looking at what is possible in the laboratory, what is possible in theory, and what is possible from a practical perspective, particularly with respect to safety and packaging issues," says Dr. Pellegrino. "We tried to set the bar high enough that clearing it would mean the competitor had done something significant, but not so high that no one could realistically meet it," he explains.

The execution team drew up a set of rules that reflected the agreed-upon WPP criteria. "It was important for us to make the rules very clear, objective, and definitive. They reflected a reasonable degree of difficulty, and we worked with all the entrants to make sure they had enough information to meet the safety and design criteria," says Mr. Hopkins. In planning and executing the WPP competition, the slogan "safety first" had a literal meaning. The safety evaluation team was "top-notch," says Dr. Pellegrino, comprising about a dozen members from the Army, Navy, and Air Force laboratories in all areas of power generation, including electrochemical (batteries and fuel cells) and conventional engine systems. One of the safety evaluation team's early tasks was to publish a list of acceptable and unacceptable reactants. Registrants were required to submit a fuel plan, or list of chemicals they planned to use, and a system design. Each of the entries was then evaluated for completeness of required technical data and safety. "The whole premise of the competition was to make the lightest-weight system that met the energy density criteria, and safety features necessarily add weight. So we knew that competitors might compromise safety by trimming system components or taking shortcuts," says Dr. Terrill Atwater, Senior Research Chemical Engineer in the Communications-Electronics Research, Development, and Engineering Center (CERDEC) at Fort Monmouth.

"One of the safety evaluation team's greatest concerns at the outset was the unconventional groups that don't normally do business with the government. Though virtually all the competitors were professional and technically savvy, they might not place the same emphasis on safety that we do in the DoD," says Dr. Atwater. "We also realized that some competitors might try to pull an idea out of the drawer that had previously been discarded for safety reasons." As the competitors developed and tested their systems, and the WPP safety evaluation and execution teams continued to interact with them regarding technical and safety issues, the number of entrants began to dwindle. Some teams realized their systems would fall short of the competition metrics, while others ran out of money or did not have the wherewithal to keep going. In other cases, they concluded that their proposed technologies needed more time and effort to mature before practical application would be possible.

> "One of the beauties about America is that we have an incredible wealth of innovative people"

Without exception, however, the entrants were technical pioneers seeking to open up new territory with their imaginations. "One of the beauties about America is that we have an incredible wealth of innovative people," remarks Mr. Shaffer. "Every idea that was presented reflected a different approach, from high-energy density batteries to hybrid fuel cells."

Competing Concepts Go Head-to-Head in the Desert

As the capstone event drew near, DDR&E expected 48 teams that had met all the data submission requirements to show up at the Marine Air Ground Combat Center. Lead test engineer Todd Browning, an employee of ARL contractor Alion Science and Technology, was given responsibility for setting up the bench and field tests that would determine the winner. "We had to be prepared to test an unknown number of systems and measure every competing system equally and simultaneously," recalls Browning. To do that, he arrived at the test site three weeks early to commence building the engineering test operations. It was an exciting opportunity, Browning says, but one that was highly demanding and sometimes challenged his own endurance. "I was there in the desert for 36 days, between the setup and the event itself, and sometimes the temperature went close to 120 degrees." Browning

Rayovac Team inflates a boat during final field tests.

and his team had a critical role in the competition, according to DDR&E Program Manager Karen Burrows. “There was no opportunity for a do-over. We could not have any slip-ups in testing, and it was necessary that we treat every system with the utmost care and respect it deserved.” The testing team prepared enough capacity for 40 systems in an initial 92-hour bench test that simulated loads up to 200 watts and was capable of measuring two voltage channels for each system. “After we set up everything, we ran the full 92-hour bench test several times to make sure no test equipment would fail. We also designed special field test monitors that would attach to the vests, allowing the systems to move among the field test stations. We went through every test channel, calibrated it, ran sample tests, and then recalibrated all the equipment,” says Browning.

DuPont/Smart Fuel Cell system powers computer laptop during final tests.

The bench tests were to be followed by nine field test stations that would draw on the finalist systems’ remaining power to run equipment with varying power draws. According to ARL’s Hopkins, the following battlefield equipment was chosen for the field test phase:

- Heated clothing
- Land warrior system (an ensemble of equipment integrated into a system worn by soldiers and containing a helmet-mounted display, computer communications equipment, GPS, and a host of other battlefield technologies)
- Man-portable radio
- Oxygen-deficient chamber
- Personal cooling garment
- Laptop computer
- Portable ventilator
- Water purification system
- Inflatable boat

The first day onsite at Twenty-nine Palms, only 20 teams showed up, rendering excess testing capacity. As a result, WPP officials offered bench testing for “nonprize-eligible” second systems, as well as field testing for systems that had not achieved the required metrics during the bench test, but still had power left to tackle the gauntlet of nine tasks, allowing these competitors to collect additional data. “I was greatly impressed by the caliber of the bench and field testing,” says Jack Taylor, Associate Director for Land and Sea Systems in DDR&E and a member of the adjudication team. “The execution team was a highly capable and motivated set of individuals, many with PhDs, and representing all of our military departments.” During the testing operations, the adjudication team monitored things closely. “We reviewed the competition’s progress on a daily basis, checking the appropriateness of the testing processes and the adequacy of data and analyses. We also validated the final outcomes,” says Taylor. “It was quite a feat in terms of manpower, equipment, and environmental conditions,” Browning comments.

The “Lightest and Brightest”

At the conclusion of the field test phase, five teams had fulfilled all competition metrics, after 96 hours of power draw, making them eligible to receive one of the money prizes. To determine the three actual winners, it all came down to fractions of weight:

Ranking	System	Weight (kg)	Prize
1	DuPont/Smart Fuel Cell (SFC) M-25 system	3.762	1st
2	AMI system (Adaptive Materials Inc.)	3.790	2nd
3	Jenny 600S (Capital Connections) system	3.865	3rd
4	Ultralife system	3.989	
5	Ultra Cell system	3.990	

Three more teams demonstrated energy densities in excess of the 480 watt hours per kilogram minimum energy density goal but were deemed ineligible when their systems did not meet all of the competition metrics for 96 full hours of operation. The incredibly low weights of these three systems, though, caught everyone’s attention:

System	Weight (kg)
Rayovac system	3.428
AMI second-entry system	3.076
Lockheed Martin system	2.397

The four top finishers were all variants of fuel cell systems, led by DuPont/SFC’s fuel cell-methanol hybrid. According to team leader Dennis Kountz, DuPont evolved its trademarked Nafion®* material for the component membrane electrode assembly. “We fine-tuned the material in order to build a fuel cell stack that was as efficient a power source as possible. Our partner’s advanced technology allowed our system to handle the challenging power draws, voltage requirements, and environmental conditions. After all the testing, we ended up with a fully charged battery and excess methanol fuel.”

Rayovac’s entry was a lightweight lithium-carbon monofluoride (Li/CFx) battery, the company’s most powerful battery pack to date. Although it did not win a prize, its weight and power outputs were impressive. “The Rayovac team basically made a conventional battery that demonstrated a several-fold increase in energy density,” notes Mr. Shaffer. “Our goal was to identify promising battery designs that can be further developed into something that is fieldable on a soldier and is safe,” says Rayovac team leader Greg Davidson. “The energy density and power control requirements eliminated other types of batteries from the competition, allowing us to show off a little bit more.”

These developments, Mr. Shaffer believes, will be showing up in technology solutions that will not only transition to the warfighter but also help solve the critical energy and power issues facing America. “If we can spur the commercial market through these types of competitive activities, that’s a great thing,” he says.

Ultralife Team breaks after successful completion of field tests.

The Merits of a Competition

Ideally, a prize competition fosters both the levels of entrepreneurialism and the collaboration needed to spur scientific discovery and engineering development. By all accounts, the WPP competition provided fertile ground for information sharing and data collection. "It was a very good networking opportunity," says Scott Schoeffel, leader for the fourth-place Ultralife team. Out of Navy special operations for less than a year, Mr. Schoeffel knows firsthand how power needs can affect mission success. "I was able to speak with most of the fuel cell researchers who were competing. There was a lot of information sharing about some pretty intriguing ideas, although no one divulged anything proprietary," Schoeffel adds.

All the teams that entered the WPP competition "will have a better perspective on the type of functionality needed in the battlefield environment as a result of their participation and can go on to continue pursuing lightweight, portable power solutions," notes ONR's Dr. Pazik. The sophisticated testing regime provided finalists with extraordinarily useful data for future R&D efforts. "These were complex tests done in the kind of conditions that the competitors probably would not have had the opportunity to replicate themselves," says Mr. Hopkins. "We moved the laboratory out into the desert, and the type and accuracy of the data we collected, and the extreme environmental conditions in which they were collected, has never been done before with respect to wearable power systems," Hopkins continues.

The interactivity that is one of the hallmarks of the prize program format provided another benefit to the WPP participants: access to DoD. Competitors worked with tri-service experts throughout the competition, and those who came to the final event also mingled with many DoD senior officials and acquisition officers. Ultralife's Scott Schoeffel notes, for instance, that he had the chance to speak personally with DoD Undersecretary John Young for almost an hour during the capstone event. "The key for us is that we reached out to folks who were able to make some startling advances in power sources and management technologies," Mr. Shaffer says.


Rayovac Team member demonstrates system operation in prone position.

Redeeming DoD's Investment

According to Dr. Pellegrino, the EPTI and the individual R&D organizations in each service branch are culling through the data with an eye toward following up on the most promising wearable power technologies demonstrated during the competition. Some of these technologies are already known to the DoD, and variants are being funded through mechanisms such as the Program Executive Office (PEO) structure. Other approaches are in various stages of R&D.

"In that sense, the competition validated our investments in this area," says Dr. Pellegrino. "We found that we have a robust awareness across the DoD power and energy community of many of the approaches, techniques, and materials that were demonstrated. That tells us we are well-connected with the R&D community and have been investing in the right areas."

"Surfacing novel approaches from the competition entails diving into the metrics and identifying matches with our own goals for where wearable power technologies should be three to five years from now," says Dr. Ed Shaffer. In any technology competition, he says, ideas will surface that are not solidly grounded in science and engineering. In other cases, people will try some seemingly odd ideas that may turn out to have a substantial payoff. "By diving down into the data, we may pinpoint materials or approaches that were not presented as a whole system but could offer us some options for future exploration."

One private inventor who showed up at the capstone event is investigating electrostatic power generation (boot power) and has been invited to brief his ideas to ARL researchers. Nevertheless, "Nothing emerged from way out in left field, but there were some interesting twists to the technologies that were brought forth," remarks Dr. Pellegrino.

INSPIRING NEW INNOVATORS

Informing the public and the broader scientific and entrepreneurial communities about wearable power was yet another positive outcome. "The prize program was successful in enticing both users and developers to broaden their thinking about the power outputs that are possible in a small package and the range of areas in which these technologies are applicable," says Dr. Pellegrino.

The WPP competition was also successful in an area that it did not initially set out to exploit. The DoD S&T enterprise needs to replenish its ranks of scientists and engineers with new talent. By their exposure to DoD technical experts throughout the competition, many of the younger competitors were introduced to the defense research community as a prospective employer that offers some of the best technical challenges that exist today.

Also mindful that a better informed public includes future generations of scientists and engineers, Karen Burrows masterminded a "Kid's Day" on October 3, the day between the end of the bench test and the culminating field test. "This special event helped inspire young students to consider careers in defense research and engineering," says Burrows.

Major Lincoln agreed to lead the 4-hour event that brought some 300 kids from three local schools to the Marine Air Ground Combat Center for an educational outreach event dubbed "The Future Charges Up Here." Among other activities, senior engineers led groups of students on tours of the competition area and the Technology Showcase tent, where they were able to see and

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even touch some of the latest technologies being transitioned to the warfighter. "It is important to perk up kids' interest now so that, when they make choices in school, these technologies will stick in their minds as something cool that they could be a part of," says Major Lincoln. "Kids' Day was a huge hit."

"OUTSTANDING"

"This was a competition in the truest sense of the word. We set clear, objective metrics and took great pains to make sure every competitor got the same experience, whether they were a single individual or a large corporation. That was something we worked very, very hard to achieve," says ARL's Hopkins.

Although one would expect the first-place team to be pleased with the competition, DuPont/SFC team leader Dennis Kountz also understands the enormity of the effort. "We were impressed with how DoD ran the competition because we thought they were biting off a huge task. They did an outstanding job."

DuPont/Smart Fuel Cell M-25 Team with $1M award.

"The results exceeded our expectations on many fronts," says DDR&E's Burrows. "We wanted this inaugural prize competition to raise the public's interest and increase their engagement in this critical technology area, and we did that."

Adds Dr. Rees, "The real winners from this competition are our ground warfighters. The wearable power systems demonstrated at the competition show great promise for dramatically reducing the weight of the power systems they must carry while performing their critical missions."

ACKNOWLEDGEMENT

All photos by Larry Shank, US Army Research Laboratory.

NOTE

* Nafion is a registered trademark of E. I. du Pont de Nemours and Company Corporation.

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Assuring Supply through New Energy Alternatives and Opportunities

The Defense Energy Support Center

Kelly Widener
Defense Energy Support Center
Fort Belvoir, VA

INTRODUCTION

The Defense Energy Support Center (DESC), a field agency for the Defense Logistic Agency (DLA), has the unique mission of providing the Department of Defense (DoD) and other federal civilian agencies with energy solutions to support missions and operations worldwide. This mission requires DESC to actively engage in different energy field opportunities, while continually expanding its support role by exploring emerging technological advancements and energy and fuel commodities to ensure that its customers receive the most effective and efficient products and services.

In the current operational environment, supporting customers located around the globe requires the ability to not only supply energy and fuel commodities to remote locations but also to provide sustained supply of those commodities. Factors such as impact to the environment, energy use, fuel prices and commodity availability and development are all considered while sustaining the energy supply. Volatility, changes or sensitivities in any of these, or other factors further support the need for ongoing expansions of resources, research focused in the energy and fuel field, and efforts to establish alternative energy sources and opportunities.

Filling the role as an energy and fuel supplier, DESC is supporting programs and initiatives that involve renewable energy, synthetic paraffinic kerosene, waste-to-energy technology, algae oil, and the ASTM B20 specification for commercial biodiesel. DESC is reaching forward to not only assist DoD entities with facilitating their renewable projects but also to support the ongoing efforts for federal civilian agencies as they work to achieve federally-mandated goals. These programs focus on increasing the use of energy alternatives and technology such that it can become infused in the DESC mission.

SUPPORTING ENERGY REQUIREMENTS

Through contract solicitations, procurement and administrative contractual oversight, DESC works to assist its DoD and federal civilian clientele in the procurement process so they can attain their energy requirements, whether operational or political in nature. The procurement process for required support of these initiatives is a challenging one, and DESC personnel provide technical and often innovative expertise to acquire the necessary resources. Following the development of specific solicitations that meet needed energy and support requirements, DESC reviews submitted contract proposals from capable industries and companies, awards the contracts, and maintains contractual oversight until the contract expires. In some circumstances, DESC is able to consolidate several energy requirements into one solicitation, supporting multiple customers at one time and then overseeing their energy sustainment needs for the contract duration.

BRANCHING INTO RENEWABLE ENERGY

DESC recently developed the Renewable Initiatives Branch within its Installation Energy Business Unit. The branch provides contracting support to assist military and federal civilian agencies with projects intended to use renewable energy sources to supply power to installations.

Solar Energy and Hydrogen

The Defense Energy Supply Center has been involved with several efforts to provide power to facilities from the renewable solar resource (see Figure 1). For example, DESC is collaborating with the Department of Energy's (DOE) Princeton Plasma Physics Laboratory to construct a solar photovoltaic (PV) array at the laboratory. Rooftop and ground-mounted PV arrays will be constructed to convert solar energy to electric power to supply the laboratory with a renewable energy source.

Figure 1. Photovoltaic array.

DESC also supports the use of PV systems at DLA locations, such as the Defense Distribution Depot San Joaquin in Tracy, California. These systems will generate electricity to create hydrogen to run warehouse forklifts (see Figure 2) during a two-year demonstration project. This program seeks to expand the use of hydrogen as an efficient and effective energy carrier.

Forklifts used in DLA warehouses are currently powered by lead acid batteries or propane. The use of hydrogen fuel cells would decrease required maintenance space within the warehouses where the batteries must be charged and later allowed to cool. Unlike forklifts that are powered with propane, forklifts powered by hydrogen fuel cells have clean emissions in which the only output is water vapor. This contributes to a healthier work environment.

There are currently three contracts under the two-year demonstration program, but DESC expects more awards in the future. Participating locations for this demonstration project include the Defense Distribution Depot in Susquehanna, Pennsylvania,

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and Robins Air Force Base, Georgia. Fuel cells have been implemented to power approximately 40 forklifts at Susquehanna and approximately 20 at Warner Robins.

These demonstration projects have the potential to expand the traditional hydrogen energy role and open opportunities and operational settings where hydrogen may replace less efficient energy sources.

Figure 2. Fueling a forklift with hydrogen.

A prototype project involving DESC is now providing waste-to-fuel test units to six participating Army installations and one Defense Logistics Agency site. These units employ microorganisms that excrete specific enzymes which break down components of biodegradable waste into useful hydrocarbons. Essentially, biodegradable waste can be easily and efficiently converted into fuel, soil and other marketable products.

The biowaste degradation through bacterial action has the potential capability of producing longer, unique hydrocarbon strands. This bacterial action occurs while releasing hydrocarbon-based oil, which can then be processed into useable fuel; in this case diesel fuel is the targeted product. Additionally, one of the by-products made from the process is potting soil, which can be used on Army installations. Throughout the one-year testing phase, DESC will evaluate these products to determine their potential use as diesel fuel.

The test units provided to the DoD are mobile and comprised of a 45-foot trailer with ten reactor units, ten fuel receivers and a control office. The control office staff records and analyzes the biodegradable waste, bacterial strain, fuel output and energy inputs.

DESC and contracted bioenergy specialists oversee testing to ascertain and validate the hydrocarbon types produced by the test units and establish whether the fuel produced is usable. Following the one-year testing phase, these specialists will determine if the fuel output and waste breakdown is successful and ready for equipment testing.

The test units are being implemented and operated at Fort Stewart, GA; Fort A.P. Hill, VA; Fort Bragg, NC; Fort Benning, GA; Fort Lewis, WA; and Fort Drum, NY. One unit will also operate at the Defense Fuel Support Point in San Pedro, California.

Synthetic Fuels as an Emerging Energy Source

Synthetic fuels derived from the Fischer-Tropsch process are emerging as an operational fuel source for the military. The Air Force plans to complete certification testing of the Fischer-Tropsch 50:50 blend of synthetic and conventional fuels for weapons platforms and equipment by 2011. By 2016, the Air Force will be prepared to cost competitively acquire 50% of the Air Force's domestic aviation fuel requirement via an alternative fuel blend in which the alternative component is derived from domestic sources produced in a manner that is greener than fuels produced from conventional petroleum. The Air Force is working toward a goal to acquire 50:50 synthetic fuel blends to sustain half of its domestic aviation fueling requirements by the year 2016. DESC is helping the Air Force with this fuel goal by awarding three contracts to support Air Force certification efforts, and they are expecting to award more over the next few years.

The potential growth in demand of synthetic fuels requires DESC to remain proactive and anticipate future requirements. The 2009 DESC Alaska Synthetic Fuels Industry Summit is intended for this purpose. The Summit brings together DoD colleagues, energy and fuel subject matter experts, industry professionals and organizations, and political stakeholders in the Alaskan communities. The convening of these groups not only allows collaboration but also provides DESC with an opportunity to lay out the specific plan for pursuing a pilot program for Fischer-Tropsch synthetic fuels support.

The Alaska Synthetic Fuels pilot program has the goal of providing Fischer-Tropsch synthetic fuel to cover DoD JP-8 requirements in the state of Alaska. In addition, the program can potentially fulfill other DoD and federal civilian agency jet fuel and ground diesel requirements within the state.

Waste-to-Fuel

Going "green" is increasingly taking on more meaning and having greater impact in terms of supporting operations and energy sustainment. The DoD and the military services are engaging in a new initiative to reduce garbage while producing fuel by converting waste to fuel. This initiative supports one of the green initiative goals of the military branches, which is to reduce dependence on fossil fuels and operation footprints.

THE WAY AHEAD

The origin of DESC dates back to World War II, when its mission was to administer the critical petroleum requirements during the war. Currently, that mission includes supporting the DoD and other agencies in a multitude of energy solutions while assisting them in successfully achieving energy requirements, both today and through sustainment practices for the future.

Energy solutions involving wind, solar, algae and more are potential opportunities with benefits that are being tested, evaluated and implemented over time. DESC is committed to engaging in these initiatives to ensure that its customers attain their energy requirements while aiding in ongoing efforts to operate within federal mandates. These programs and others support the increasing energy alternatives and technology that is expanding and becoming infused into the DESC mission.

Ms. Kelly Widener is the public affairs officer for the Defense Energy Support Center located at Fort Belvoir, Virginia. Among her other duties, she is the public affairs officer for the center's publication *Fuel Line. Fuel Line* highlights and covers topics in the fuel and energy fields including alternative fuels and renewable energy. The publication can be found on the center's website: http://www.desc.dla.mil/.

TARDEC's Power and Energy Vision

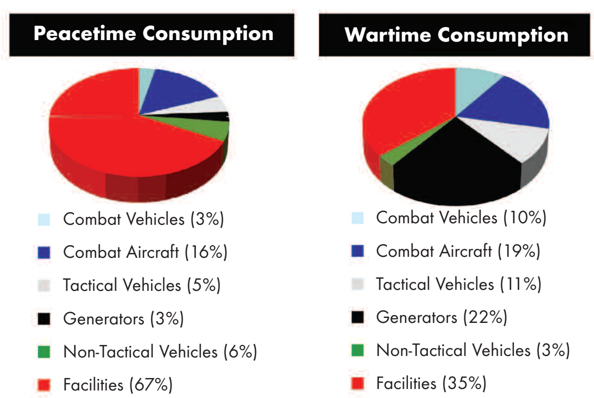
Prepared by the US Army Tank Automotive Research, Development and Engineering Center
US Army Research, Development and Engineering Command
Detroit Arsenal, Warren, MI

The Army is confronting power and energy challenges from national security issues related to foreign oil consumption, [including] the monetary and human costs of oil for DoD operations and climate change, with innovation in technology and the evolution of the current DoD fleet to more efficient combat systems. Driven by these challenges, TARDEC is taking on initiatives to lead the Army on fuel and energy with advancements in fuel efficiency, power management and an examination of how significant changes can be made from a life-cycle perspective.

– Dr. Grace M. Bochenek, TARDEC Director

The military's power and energy demands are growing rapidly. Consider the alternator in the High Mobility Multi-purpose Wheeled Vehicle (HMMWV). The current output increased from 85 amps to 400 to 600 amps in just two years. As the Department of Defense's (DoD) ground vehicle integration center, the power and energy vision of the US Army Tank Automotive Research, Development and Engineering Center (TARDEC) is focused on how energy sources can be connected on a flexible network to all combat systems. Energy is being studied from a layered structure perspective as four entities: generation, distribution, transfer and vehicle.

From TARDEC's perspective, vehicle power and energy are considered in terms of primary and non-primary power, energy storage, and power and thermal management. TARDEC has been exploring several options for power and energy for ten years. Some of these are highlighted in this article.



Peacetime and wartime fuel consumption.[1]

ENERGY STORAGE AND BATTERY TECHNOLOGY

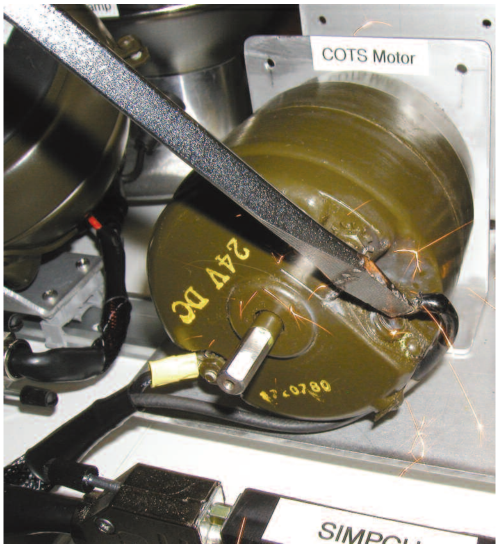
As electric power-consuming systems proliferate in modern combat operations, there is a corresponding and critical need for electrical energy storage capacity. TARDEC has created programs to develop battery technologies, ranging from safer, more effective cathode chemistries to expanding domestic manufacturing capability in partnerships with private industry, so that both can reap the benefits of safer and more cost-effective technologies. These programs include work on new cathode materials for Lithium-ion (Li-ion) cells, nanocomposite cathode materials for high power needs, and an initiative to build the first US-automated manufacturing facility for Li-ion batteries to be used in the Future Combat Systems (Brigade Combat Team) (FCS (BCT)) Hybrid Electric (HE) fleet.

High-power, high-energy density, Li-ion batteries are being designed for use in Hybrid Electric Vehicle (HEV) propulsion systems. In addition, these batteries are being considered for other critical applications including auxiliary power units (APUs), plug-in hybrids, silent watch energy storage, pulse power delivery applications and future hybridized power source design.

In July 2004, TARDEC awarded a Manufacturing Technology (ManTech) Objective program contract that seeks to improve overall battery performance, safety, and reliability and reduce the manufacturing cost of Li-ion batteries by automating the battery manufacturing process and reducing production costs. Prior to this contract, there was no industrial base for these batteries; they were fabricated to customer order and therefore, quite expensive.

The contract scope includes 1,000 process improvement tasks taking place over a six-year performance period. Among the many tasks, these objectives will be addressed: manufacture of improved electrodes, cell closure and bussing/circuit breaker, and cell filling; cell formation; battery assembly; performance and safety assessments; and development of liquid cooled modules and prismatic cells. Currently, the tasks are broken up in to five generic categories: mixing, coating and winding; electrolyte filling; circuit breaker bussing and closing; electrical formation; and battery assembly. All these major tasks have separate individual sub-tasks that are being worked in parallel. Concurrently, TARDEC researchers are also working on cell safety and performance improvement.

Target metrics for the program include reducing the cost of the 30-kilowatt-hour battery pack by 50% while significantly increasing the battery power and energy density. Technology improvements will be integrated into the ManTech effort to include new electrolyte and electrode materials enhancing high-temperature



A short-circuit protection device used to protect equipment when military vehicles increasingly exceed the electrical power generation capability available for mission-critical equipment. (US Army TARDEC photo)

stability. Inherent within the cell structure, new circuit breaker technology that reduces the risk of overcharging and venting will also be integrated into the battery.

Another ManTech-related project the Army Research Lab is working in partnership with TARDEC is the development of a fire-retardant electrolyte and thin electrode materials to increase cell power density. One recent program achievement is the VL34P cell, an upgrade from the VL30P cell, that offers a higher-powered, higher-density cell with improved performance in several areas: a 14% improvement in energy density, an 11% improvement in weight, a 75% improvement in power density and a 63% decrease in cell labor hours.

All tasks are on schedule and proceeding according to plan. Also, processing adjustments are being made to accelerate key areas, such as battery assembly tasks, while equipment is being purchased and installed and process trials are being conducted. In addition, the Li-ion automated manufacturing facility is being reconfigured and streamlined in accordance with Lean Six Sigma principles to decrease labor hours, automate processes and reduce costs.

Eventual benefits of these innovative production processes and products will be affordable, high-power and high-energy density Li-ion batteries suitable for traction and pulsed power applications. Pulsed power applications, such as lasers, could use Li-ion batteries as a power source to provide direct support for directed-energy weapons.

It is noteworthy that as the process improvements are being brought on-line, improved and lower cost cells are already being produced for other related military applications. This exemplifies the effect of leveraging the ManTech investment well beyond the originally defined program objectives.

At the beginning of the program, there was no automated manufacturing plant for Li-ion batteries in the US. Since then there has been significant progress in the development of the technology. The power and energy density of Li-ion batteries has been improved and the manufacturing process has been fully automated with built-in quality control procedures inherent to the production line. In addition, affordable, high-power and high-energy density battery packs for HEV dash mobility, silent watch capabilities, pulse power for electric weapons, and increased survivability are now available.

HYDROGEN AS AN ALTERNATIVE FUEL

TARDEC is a part of the hydrogen refueling cooperative program that is providing important data to the US Army and the Department of Energy (DOE) to help determine the best alternatives to fossil fuels. A hydrogen fueling station (HFS) was opened at Selfridge Air National Guard Base (SANGB), MI, and is providing valuable real-world operational data for the DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Program. This station will provide insights into the economical and technical viability of using hydrogen as a transportation fuel.

The HFS houses a piece of equipment known as a "reformer" that converts natural gas into hydrogen. The hydrogen is compressed to greater than 5000 psi and stored in gaseous tubes. The hydrogen is then dispensed through a mechanism that looks very similar to a regular gas pump. The dispenser has a nozzle and a communications cable that interacts with the Fuel Cell Vehicle (FCV) to get important refueling information, such as pressure and temperature. With that information, the dispenser calculates how full the hydrogen car's tank is and how much pressure must be applied to dispense the hydrogen into the vehicle.

An FCV looks similar to any other car, but it differs from a conventional vehicle in two primary ways. First, its exhaust is water that is potable with few to no contaminants. Second, if the FCV has been turned off for awhile, it will take a moment to charge before it can accelerate. Once driving down the road, the only indication that it is not a conventional car is the lack of

A US Marine Corps (USMC) Cougar-H MRAP vehicle stages a roadblock in the desert southwest of Lake Habbaniyah, Iraq. Traditional electrical generation methods, such as the standard engine-driven alternator, have practical limitations in output capacity that develop from the underlying physics, such as the ability to adequately cool the device in an engine compartment's harsh operating conditions and the desert climate found in Iraq. (USMC photo by SGT Jeremy M. Giacomino)

engine noise. Since relatively new technologies are being used, a comprehensive safety system is in place to continuously monitor equipment for temperature, pressure and possible leaks.

The HFS and FCVs are the result of two Cooperative Research and Development Agreements (CRADAs). Chevron entered into a CRADA with TARDEC's National Automotive Center (NAC) in 2005, which was followed by a CRADA with Hyundai Kia Motors in 2006. TARDEC also entered into an inter-agency agreement with SANGB to serve as the site for hydrogen fuel cell car testing and fueling station cold weather testing.

The SANGB facility has been a valuable part of the hydrogen FCV development and testing process because it is one of a few locations capable of providing cold weather data for FCVs and hydrogen fueling infrastructure. This project has been, and continues to be, an example of a successful public-private partnership.

A Stryker is driven robotically through the Fort Gordon, GA, range during testing. Increased power demand on vehicles creates excessive heat, which can shorten component life and increase the burden on vehicle crews when cabin temperatures rise uncomfortably, placing further electrical demands on the system for cooling. (US Army photo by Larry Edmond)

According to the *Energy Independence and Security Act of 2007*, section 246, "Not later than January 1, 2010, the head of each federal agency shall install at least one renewable fuel pump at each federal fleet fueling center in the United States under the jurisdiction of the head of the Federal agency." As a result of the CRADAs between TARDEC, Chevron and Hyundai, TARDEC is at the forefront of upholding the US Army's 25-year plan to eliminate energy waste in facilities and reduce dependence on fossil fuels on its installations.

POWER MANAGEMENT

Military vehicles increasingly rely on a suite of mission-critical electronic Command, Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance equipment that, collectively, places an increased load on the electrical system, exceeding available electrical power generation capability for a variety of mission operational requirements. Traditional electrical generation methods, such as the standard engine-driven alternator, have practical limitations in output capacity that develop from the underlying physics, such as the ability to adequately cool the device in an engine compartment's harsh operating conditions. Additionally, current initiatives to electrify vehicle subsystems promise to save fuel and extend missions but further burden electrical systems already at capacity.

M-240B machine gun mounted on a HMMWV. In such vehicles, particularly in a desert climate, increasing power demand creates excessive heat, resulting in the need for efficient power management. (US Army photo by Christopher Barnhart)

To address the need for additional electrical power, two fundamental approaches exist: use the available power more efficiently, and permit the safe incorporation of additional power sources when mission needs dictate. *Power management*, a concept that includes the hardware, software and algorithms to more intelligently control electrical power generation and usage, addresses both approaches. It is, therefore, a systems engineering approach to the efficient use of electrical power on vehicle platforms and is also an important area of research, development and engineering for current and future military vehicles.

Power management is an integral component in developing our future vehicle fleet and furthering Army transformation in the area of ground vehicle technology. As a result, the TARDEC Power and Energy Integrated Product Team has identified power management as a critical technology area. Power management meets and/or enables many current and future military vehicle requirements including:

- Power System Situational Awareness (Information)
- Power Management
- Mode-Based Load Control & Scheduling
- Load Prioritization / Reduction / Shedding / Reconstitution Maintenance Improvements
- Signature Management
- Power Optimization
- Control and Optimization of Subsystems/Power Control Units (PCUs)
- Integrated Power and Thermal Management
- Condition-Based Maintenance Notifications
- Power Imbalance
- Degrading Loads
- Problems with Power Generation or Energy Storage Devices
- Automated Maintenance Operations and Diagnostics
- Power Integration – Controlled Contribution from Various Sources
- Charge Control – Ultracapacitor and Battery Charge Control Solution
- Safety & Survivability
- Planning & Training Related to Power and Energy
- System Integration and Conformance to TARDEC Power Management Application Programming Interface (PMAPI)
- After-Action Reporting
- Interconnectivity and Interoperability

Power management research has produced prototype hardware,

An AH-64D Apache Longbow helicopter flies a mission to support troops on the ground. TARDEC has embraced the international effort for R&D of non-petroleum-derived kerosene (synthetic jet fuel) through its efforts under the *AFI*, which could benefit helicopters such as the Apache Longbow. (Photo by Air Force TSGT Andy Dunaway and provided courtesy of US Army)

software and algorithms. The primary hardware components (termed PCUs) are "smart switches" (or solid state relays) that are controlled through an embedded microprocessor. This microprocessor enables the switch to be programmed with default settings, such as the maximum current and voltages permitted, and to automatically turn off when these limits are exceeded. This smart switch protects vital equipment and the crew and permits disabling of only the equipment in danger, not the entire circuit branch. This increases the vehicle systems' operational readiness.

Communication with the PCUs is carried out through a lightweight, adaptive control network, such as a controller-area network, which is commonly used in vehicle systems. The PCUs can respond to out-of-range conditions even when communication with the central control computer has been disrupted, giving the system added robustness and capability.

The ability to communicate and control remote loads from a central computer provides an opportunity to optimize electrical power usage system-wide. Algorithms to balance power draw from multiple sources, including batteries, alternators, ultracapacitors and fuel cells, have produced overall system efficiency improvements in the range of 20% in simulations. On-vehicle implementations are planned on the Mine Resistant Ambush Protected (MRAP) RG-31 vehicle to prove the simulation results, and they are part of the Power and Thermal Management Technologies Army Technology Objective (ATO).

Given the rapid pace of technological improvements, there is a need to standardize component behavior to prevent hardware and software obsolescence. The key is to standardize functionality while allowing for variation in the actual implementation. As technology progresses, any compliant hardware and software should be easily incorporated into existing vehicle platforms. The standards-based approach is termed a PMAPI. The standard specifies the software functions, inputs and outputs, which the hardware must support. The initial PMAPI has been adopted by Program Manager FCS (BCT).

Two Small Business Innovative Research (SBIR) programs related to power management, Advanced Electrical Power Architecture (AEPA) and Advanced Electrical Thermal Management (AETM), involved producing prototype PCU and control and optimization software to control challenging vehicle electrical loads. Of particular note, the AEPA program produced a prototype power management system that was demonstrated at the Power and Energy Symposium and at TARDEC's booth at the Society of Automotive Engineers World Congress Conference in 2008. The AETM resulted in a prototype system using ultracapacitors, PCUs and control software designed to promote advanced cold start systems. It demonstrated optimization of the power available to a vehicle starter (simulated through load banks located in a cold chamber) through a combination of ultracapacitors and batteries, showing how power management can be applied to a technically challenging situation. The SBIR company is currently engaged in applying power management to one MRAP RG-31 vehicle and one Family of Medium Tactical Vehicles variant.

A CH-47 Chinook helicopter refuels in Jalalabad, Afghanistan. TARDEC supports the *AFI* objective, under which DoD/OUSD AT&L will catalyze commercial industry to produce clean fuels for military aircraft such as this one from secure, domestic resources. (Photo by SSGT Marcus J. Quarterman and provided courtesy of US Army)

THERMAL MANAGEMENT TECHNOLOGY

The DoD's increasing electrical power demand translates to an increased thermal management requirement at the component and vehicle levels. To address this growing capability gap, TARDEC is leading a new FY08 ATO that focuses on advancing and applying power and thermal management technologies to military systems.

The ATO's goal is to develop technology that improves electrical power usage. Specifically, the improvements are aimed at reducing power loss at the component level and increasing the efficiency of waste-heat removal in current and future tactical and combat ground vehicle systems. Power management has been a subject of serious work for the past few years, but recently it has become clear that any work completed in this field immediately impacts heat-rejecting systems. Therefore, to maximize efficiency, this program will be tailored to address both power and thermal management as dependent factors.

Although the Power and Thermal Management program is only scheduled for three years of research, thermal management was identified as an important technology area needing additional investment. Fundamentally, this project is designed to provide working solutions for soldiers. An intelligent power management system with integrated thermal management will reduce the crew burden by automating certain processes and will ultimately result in more available power for soldiers to accomplish their mission.

Modeling and simulation (M&S) can be used to seek out various technologies. Thermal modeling toolsets, such as the Cooling System Evaluation Tool, were developed to increase TARDEC's core capability in thermal M&S. HE thermal demands motivated the development of a carbon foam cold plate for power inverters, and carbon foam radiators were developed for HMMWVs and compared to a baseline radiator. Thermal management has increased in importance with the increase in electrical equipment in crew compartments and also with the recent emphasis on HEVs and the increased use of power electronics. TARDEC's M&S and test and evaluation efforts seek to understand the component- and system-level impacts of advanced heat-rejecting materials and cooling methodologies, with application to power electronics. The overall system will improve electrical stability and efficiency and increase heat rejection by linking power and thermal management strategies into an integrated onboard architecture.

There are several ongoing programs building on past efforts. Some of these efforts include the optimization of power sources and loads using artificial intelligence, a CRADA that incorporates thermal data into the existing models, and several enhancements to the Electronic Power Architecture Systems Integration Laboratory to accommodate high-voltage components, prepare for thermal testing of power electronic devices and verification of thermal component modeling.

This new ATO program will focus on researching methods to increase component life, reduce and recover waste heat energy, extend silent missions, increase battery reserve and increase operating temperatures of solid state electronics. Several of the planned future programs will be in collaboration with universities, industry and government research facilities. Some of these programs include:

- The enhancement of a power management optimization cost function that incorporates thermal data with research into the miniaturization of power control units.
- Development of carbon foam radiators for FCS.
- Integration of phase change technology and carbon foam.
- Research on a high-efficiency waste heat recovery system using advanced materials such as depleted uranium.
- Development of nano-fluids as a coolant for prime-power and/or electrical systems.
- A power and thermal management prototype/demonstration in collaboration with the Non-primary Power Systems ATO program to integrate an APU as a power source.

Based on feedback from a Power and Energy Symposium hosted by TARDEC in 2008, power and thermal management is an area of growing interest to both government and industry. This ATO program will advance hardware and software components and systems, resulting in the Army's vision of an integrated power and thermal management architecture.

SYNTHETIC FUELS

As previously noted, the US is looking for ways to reduce dependence on foreign energy sources. High fuel costs are hitting the military as hard as consumers, so efforts such as those initiated in 2004 by the Office of the Secretary of Defense's *Assured Fuels Initiative* (AFI) to seek secure, domestically-sourced clean energy alternatives continue today.

TARDEC embraced the international effort for research and development (R&D) of non-petroleum-derived kerosene (synthetic jet fuel) through its efforts under the *AFI*. The *AFI* objective is that the DoD/Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD (AT&L)) catalyzes commercial industry to produce clean fuels for the military from secure, domestic resources. DoD's role as the catalyst in attaining this vision is threefold:

- Engage in the development of alternative fuel specifications.
- Certify, qualify and demonstrate the use of alternative fuels in DoD tactical vehicles, aircraft and ships.
- Implement the use of alternative fuels in DoD tactical vehicles, aircraft and ships operating throughout the continental US.

TARDEC has been a key participant in the *AFI*, beginning in 2003 with laboratory evaluations of synthetic fuel, namely Fischer-Tropsch (FT) synthetic kerosene. The coordination of DoD synthetic fuel specification development with that of the commercial aviation industry was spearheaded by TARDEC's NAC in May 2003 and continued into 2007. This coordination was established through the Aviation Committee of the Coordinating Research Council (CRC-AC), which includes representation from the airframe and jet engine original equipment manufacturers (OEMs), jet fuel producers and government agencies such as the Military Services, Defense Energy Support Center, NASA and Federal Aviation Administration.

Although CRC-AC is not responsible for regulation, hardware or fuel development, or setting standards, its efforts to direct engineering and environmental studies indirectly influence these areas. ASTM International, which maintains the fuel specification used by US commercial aviation, looks to CRC-AC to provide guidance regarding non-petroleum-derived kerosene and its potential suitability for use by US commercial aviation.

The effort under the *AFI* carries forth today, underpinned by the Air Force objective as stated by former Secretary of the Air Force Michael W. Wynne in July 2007:

> *"The Air Force is committed to completing its testing and certification of our aircraft fleet for alternative fuels by 2011. Working with industry, we can accomplish this goal. Once accomplished, we look forward to buying domestically produced synthetic fuel at competitive market prices from manufacturing facilities that engage in effective carbon dioxide capture and reuse."*

In January 2008, CRC-AC published a report, *Development of the Protocol for Acceptance of Synthetic Fuels Under Commercial Specification*. This protocol is intended to establish that once a synthetic fuel (including blends of synthetic and petroleum-derived fuel) is accepted as suitable for use by the aircraft engine OEM and written into fuel specifications and/or service bulletins, the fuel will automatically be an approved fuel under the fuel specification for US commercial aviation (ASTM D1655-08, *Standard Specification for Aviation Turbine Fuels*). This is a significant *AFI*-supporting milestone, because having an agreed on and documented protocol for acceptance of synthetic jet fuel is a critical step in establishing a market for it.

Between the commencement of TARDEC evaluations of synthetic kerosene and coordination of fuel specification development through CRC-AC, NAC represented TARDEC efforts targeting *AFI* goals in other forums with international ties. In 2003, 2005 and 2007, NAC participated in the biennial conference of the International Association for the Stability, Handling and Use of Liquid Fuels, which promotes research and experimentation on scientific and operational factors affecting the stability, handling and use of fuels from manufacture to end use and disposal. The most recent conference in October 2007 focused on alternative fuels. More than 50 speakers presented highlights from their R&D areas, including FT synthetic fuels.

NAC presented two posters, one of which highlighted TARDEC evaluations of FT synthetic kerosene. The second poster highlighted results of a study examining the potential to use up to 50%, by volume, of FT synthetic kerosene in blends with the jet propellant 8 (JP-8), a commercial jet fuel (Jet A-1) with military-approved additives that is typically used at the five US Army installations included in the study.

NAC also participated in the 2005 Aviation Fuel Forum of the International Air Transport Association (IATA), an organization comprised of 270 member airlines representing 94% of scheduled international air traffic and with a mission to lead, represent and serve the airline industry. IATA's Aviation Fuel Working Group (AFWG) formulates the technical basis for an international specification guide for aviation turbine fuels that IATA develops and maintains. In May 2005, NAC introduced the AFWG to *AFI*'s vision and goals. At that time, the AFWG had already been considering use of synthetic jet fuels for commercial aviation, primarily based on the successful use of FT kerosene in blends with Jet A-1 at Johannesburg International Airport in Johannesburg, Gauteng, South Africa. Since JP-8 is derived from Jet A-1, it is essential that both the US military and the commercial aviation industry nationally and worldwide are aligned in requirements for synthetically produced Jet A-1.

Through its involvement with forward-thinking projects such as the *AFI*, TARDEC is, once again, asserting its position at the forefront of emerging alternative energy R&D and implementation.

ACKNOWLEDGEMENT

The following individuals contributed to this article: Dr. Grace M. Bochenek, TARDEC Director; Thomas Mathes, TARDEC Executive Director of Development; Sonya Gargies, TARDEC Energy Storage Team Leader; Orest Tarnavsky, TARDEC Ground Vehicle Power and Mobility (GVPM) ATO Manager; Patsy Muzzell, Acting Team Leader and Project Engineer for the TARDEC NAC Assured Fuels Initiative team; Mary Goryca, TARDEC Team Leader for Power Plant Integration; Mark Stanczak, President, Global ET; and Carrie Deming, BRTRC.

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TARDEC is the nation's laboratory for advanced military ground systems and automotive technology. A leading technology integrator for the US Army Materiel Command's Research Development and Engineering Command (RDECOM), TARDEC is headquartered at the Detroit Arsenal in Warren, MI, located in the heart of the world's automotive capitol. TARDEC is a major element of RDECOM and a partner in the TACOM Life Cycle Management Command. As a full life-cycle engineering support provider-of-first-choice for all DoD ground combat and combat support weapons and vehicle systems, TARDEC develops and integrates the right technology solutions to improve Current Force effectiveness and provide superior capabilities for the Future Force. TARDEC's technical staff leads research in ground vehicle survivability; mobility/power and energy; robotics and intelligent systems; maneuver support and sustainment; and vehicle electronics and architecture. TARDEC develops and maintains ground vehicles for all US Armed Forces and numerous federal agencies.

Navy and Industry Pursuing New Power and Propulsion Methods

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The Navy is testing new concepts in power generation, conversion, and distribution to make ships more efficient, economic, and combat-effective. Ships being developed in both the near term and long term will have a variety of newly designed propulsion systems depending on their size, mission, and ship characteristics. This article discusses some key technologies on the horizon.

ALL-ELECTRIC INTEGRATED PROPULSION

An integrated power system (IPS) is an all-electric architecture, providing electric power to the total ship with an integrated plant. IPS enables a ship's electrical loads, such as pumps and lighting, to be powered from the same electrical source as the propulsion system (e.g., electric drive), eliminating the need for separate power generation capabilities for these loads.

To meet the increased power demands for new sea-based weapon systems, next-generation surface combatants, such as the DDG 1000 *Zumwalt*-class of guided missile destroyers (see Figure 1), will feature all-electric propulsion and an entirely new way of distributing power for propulsion, ship service, and combat capability. *All-Electric Propulsion* is a promising technology for both naval and commercial marine applications. On the DDG 1000, power will be generated by two large gas turbine generators and two smaller ones. By using efficient power management, power is available to handle all of the electric loads throughout the ship, including potential future power-hungry weapons such as rail guns or directed energy weapons.

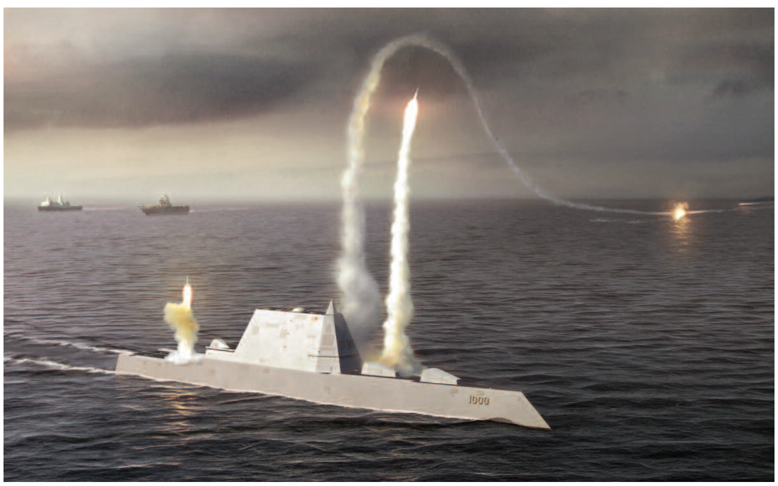

Figure 1. An artist's rendering of the *Zumwalt*-class destroyer DDG 1000, a new class of multi-mission US Navy surface combatant ship designed to operate as part of a joint maritime fleet, assisting Marine strike forces ashore as well as performing littoral, air and sub-surface warfare. (Photo courtesy of US Navy)

The combat value of an electric ship goes well beyond weapon capability and capacity. There are significant efficiencies and redundancies. At full power, DDG 1000 will achieve speeds up to 30 knots. If one of the main turbines is lost, the plant can be isolated and still achieve 27 knots. Since a warship usually cruises at reduced power once it has arrived on station, normal station-keeping can be accommodated with the two small turbines to save fuel and reduce radiated noise. The power previously trapped in the propulsion train can now be directed to enhance combat capability and mission flexibility. At lower speeds, *Zumwalt* has a surplus of power that can be made available as needed. Further advantages include the elimination of maintenance-intensive and high-temperature auxiliary steam systems, reduced noise and vibration, and better fuel efficiency.

Among the major advantages of electric drive for naval ships is that the prime movers, whether gas turbines or diesels, do not need to be located in a central machinery space or mechanically connected to the propeller shaft as with traditional propulsion systems. Instead, the engines can be located anywhere in the ship, distributed throughout the hull, and connected to generators to supply power. This power can be fed to a central bus that can be used for propulsion.

An all-electric integrated propulsion system enables more design flexibility in terms of engine placement. For example, the engines can be placed in the bow, stern, or even in the superstructure for smaller engines. One of the advantages of distributed power in a warship is survivability. If an engine incurs

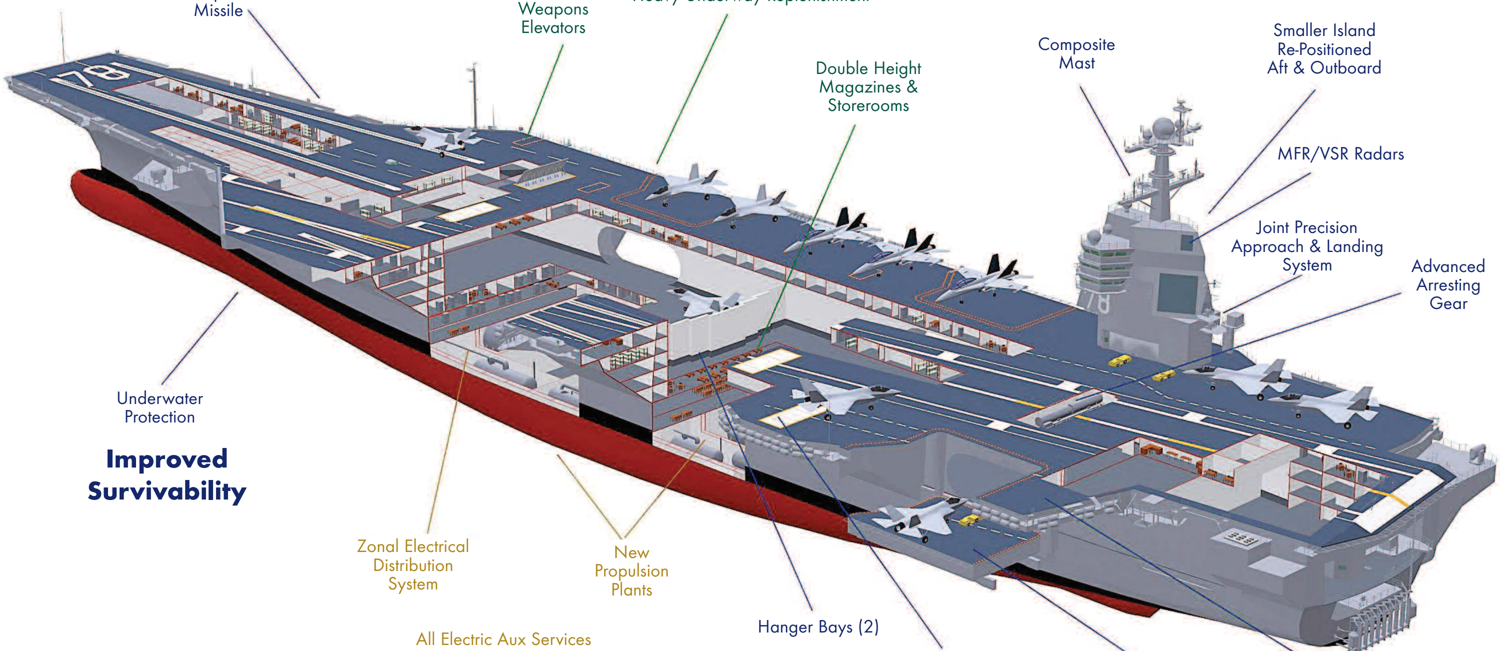

Figure 2. A conceptual rendering of CVN 78, the first of a new generation carrier design (CVN 21) for the US Navy, underway at Northrop Grumman Newport News. Innovations for the next-generation aircraft carrier include an enhanced flight deck with increased sortie rates, improved weapons movement, a redesigned island, a new nuclear power plant, and allowance for future technologies and reduced manning. (US Navy illustration courtesy of Northrop Grumman Newport News Shipbuilding)

damage or is incapacitated in one part of the ship, that part of the distribution system can be isolated while power can still be generated and distributed throughout the rest of the system. The DDG 1000 will be powered by Rolls-Royce MT30 gas turbines, which is based upon the Rolls-Royce "Trent" engine that powers the Boeing 777 airliner. The aviation version of the engine has a demonstrated reliability of 99.98%. The 'marinized' version of the MT30 has 80% commonality with the Trent 800 but is shock-mounted and has different blade coatings for operation in a saltwater environment. This engine is also serving today aboard the new Littoral Combat Ship *USS Freedom* (LCS 1). *Zumwalt* will also have a smaller gas turbine, the Rolls-Royce 4500.

DDG 1000 power generators produce 4,160 volts alternating current (AC), which is rectified to direct current (DC) that allows ship service power distribution to be tailored to the ship's needs. There are three primary advantages to DC. First, DC uses solid state power conversion that supplies loads which are converted back to AC and is a cleaner way to supply power. Secondly, many of the combat systems' loads are DC. Finally, it enables power to be shared and auctioned. DC enables uninterrupted power even in the occurrence of a casualty.

The DDG 1000 will employ fixed pitch propellers. Controllable pitch propellers and their associated complex hydraulics are not required since the motor, and thus the shaft, can be electrically reversed. But novel approaches to propulsion are being considered for future combatants.

Other new naval ships are also adopting integrated electric power systems. The next-generation CVN 21 aircraft carrier, the *USS Gerald Ford* (see Figure 2), will have a newly designed nuclear power plant and all-electric systems and propulsion. The next amphibious assault ship, the *USS Makin Island* (LHA 6), will feature a combined gas turbine and electric propulsion system.

The surface combatant IPS propulsion engineering development model (EDM) for DDG 1000 is being tested at the Land-Based Test Site (LBTS) at the Ships Systems Engineering Station in Philadelphia. The test site has been used to evaluate different configurations and motors. The test program validates key system metrics such as torque, speed and power output, and specific fuel consumption for the various configurations.

The Navy has tested the 18-megawatt (MW) advanced induction motor (AIM), which will be the baseline for DDG 1000, produced by Alstom at the LBTS. This is essentially the same system installed on the Royal Navy's new Type 45 destroyer, the *HMS Daring*, which has just been commissioned. The IPS features Integrated Fight through Power (IFTP), a fully automated DC Zonal Electric Distribution System (DC ZEDS) that provides flexible, reliable, high quality power to all shipboard loads. Other configurations are also being tested. The IPS system is fully automated with little operator intrusion. The testing at

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the LBTS will validate that the DDG 1000 IPS will automatically take appropriate corrective action if there is a malfunction or casualty without the input of an operator.

Engineers at the LBTS have also tested a 36-megawatt permanent magnet motor (PMM). PMM has greater power density than the AIM and may be used in future ships.

Many studies were performed on different combinations of gas turbines. The purpose was to avoid development of new gas turbines that were not qualified and in service or on their way into service.

Although there are advantages to distributing the power system throughout a warship hull, the size and weight of the various components has usually necessitated keeping the propulsion equipment low in the ship for stability reasons. The DDG 1000 engineering plant layout is relatively conventional because of the air intake, exhaust, and drive arrangement.

DRS Technologies and General Atomics Electromagnetic Systems are developing a hybrid electric drive which permits a smaller service gas turbine to power a permanent magnet motor that can power the ship at slow or "loiter" speeds. Using a smaller turbine can result in significant fuel savings. Furthermore, the motor can be reversed to function as a generator when propulsion gas turbines are online.

Overall, integrated electric drive offers ship designers and operators a plant flexibility that does not exist with mechanical drive systems. However, trade studies must be used to select the appropriate power and propulsion system for each ship.

There are some ships with partial electric drive or hybrid electric drive mechanical drive systems. These include the operational Type 23 frigates; the European Multi-Mission Frigates (FREMM), a joint program between France and Italy, which are now in construction for France, Italy, Morocco and Greece; and the amphibious assault ship *USS Makin Island* (LHD 8), now undergoing trials.

Despite the advantages, there are not a lot of electric drive warships in service. The new generation of electric ships has yet to prove themselves. The DDG 1000, Royal Navy Type 45, and T-AKE propositioning ships are examples of all-electric warships, but they are still in the design phase, under construction, or just entering service. Even though there is significant interest in electric drive systems, there are only a relatively small number of ships actually under construction and in operation.

SUPERCONDUCTING MOTORS

American Superconductor and Northrop Grumman have recently tested a 36.5-megawatt high-temperature superconductor (HTS) ship propulsion motor at the LBTS. The motor uses HTS wire that can carry 150 times more power than copper wire used in more conventional motors. The advantage is more compact propulsion systems which have greater power density. Superconducting wire can carry more current and generate higher magnetic fields in very small areas and thus can result in a significantly smaller motor. In other words, more power is available from smaller, lighter motors. That means Navy ships can carry more fuel and munitions and have more room for crew's quarters and weapon systems.

General Atomics' (GA) superconducting DC homopolar motor for propulsion applications is small and light compared to traditional and superconducting AC motor systems. This motor uses low-temperature supercooling that employs gaseous helium to maintain the superconducting wire within the motor at 5 Kelvin, which is almost absolute zero. Since some materials are much better conductors at very cold temperatures, and with virtually no electrical resistance supercooled conductors make for much more efficient motors. A comparable high-temperature supercooled system operates between 40 and 75 Kelvin, depending upon the technology chosen. Refrigeration at higher temperatures is easier, but the high-temperature superconducting material is not as easy to produce and is much more expensive than the superconducting niobium-titanium wire in the low-temperature motor. Niobium-titanium wire is the most widely used and available superconducting wire in world-wide commercial applications.

GA has built a 5,000 horse-power (HP) motor which is 4.5 feet in diameter. This technology is slender, light, and fuel-efficient and can be more readily adapted to propulsion pod applications.

Additionally, while superconducting AC motors have similar costs to the superconducting DC motor, there is no need for power inverters and the associated electronics to switch DC to AC.

Propulsion Pods

Most marine motor applications are located within the hull and coupled to a shaft to turn a propeller or waterjet impeller. Electric power can also be used for propellers or waterjets but can also power propulsion pods, which can be located outside the hull.

Pods provide better maneuverability to ships entering and leaving port or maintaining a precise station. With a significant amount of propulsion equipment located outside the hull, more room is available inside the ship for other purposes. Also, the signatures could be mitigated if the propulsion system was isolated inside the hull.

Cruise ship pod systems, such as "Mermaid" from RRAB (a joint venture with Rolls-Royce AB and Alstom) and ABB's "Azipod" systems, can rotate 360 degrees and eliminate the need for rudder assemblies. With a pod, the motor is in the pod, while an azimuthing thruster has the motor located in the hull. The Royal Navy's *Echo*-class of survey vessels uses electric azimuthing thrusters. Pods were considered for *Zumwalt*-class ships but ruled out because of their size.

The US Navy has used Small Water Plane Area Twin Hull (SWATH) ships for research and surveillance. These catamarans have long and slender motors and other propulsion equipment located in the submerged cylindrical buoyant hull sections, but prime movers can be mounted above the waterline. ThyssenKrupp's Nordseewerke has built the SWATH research vessel *Planet* for the German Federal Office of Defense Technology and Procurement. *Planet* will assess new propulsion technologies and evaluate the sea keeping characteristics of the SWATH hull form. Its electric propulsion enables it to test mine detection and undersea warfare systems and countermeasures.

Siemens in Germany is finding improved power availability and system responsiveness with high-temperature superconductors for podded waterjets applications. Siemens is also developing fuel cell technology for ship propulsion.

Figure 3. **The AESD *Sea Jet*, funded by the Office of Naval Research, is a 133-foot vessel located at the Naval Surface Warfare Center Carderock Division. (Photos by Mr. John F. Williams and provided courtesy of US Navy)**

Waterjets

While not a new form of propulsion, waterjets have not been used on larger ships until recently. They present some clear advantages for warships. Waterjets deliver rapid acceleration and can sustain high speeds. Waterjet-powered ships are extremely maneuverable and can stop quickly. They offer simplicity. The flow is constant in a single direction. Engine loading is constant, regardless of vessel speed, and waterjets do not overload the engines. There may be no need for a gearbox. Astern propulsion is applied by means of deflectors that divert the jetstream forward. Precise station keeping can be maintained with waterjets.

There are many advantages of waterjets. The most prominent advantage is the shallow draft of the system. Waterjets do not have appendages (such as propellers, shafts and struts, or rudders) that extend below the waterline. This minimizes the risk of damaging the propulsion gear from grounding or from hitting a submerged object, and it also reduces the maintenance requirements. As a result the boats can operate close to the shoreline, land on a beach for deployment of troops or equipment, or even run over submerged logs or sandbars without damaging the propulsion equipment. In addition, floating debris (such as ropes, nets, or weeds) does not pose much of a risk to the system particularly at high speed. Even though these items may be drawn into the jet unit at slow speeds, they are unlikely to cause damage and can easily be removed.

Waterjets are reliable. Like propeller-driven ships, there is still a shaft but it turns the pump impeller at a constant speed as compared to a much larger propeller. Drive shafts, gear boxes, and engines receive less stress, thus prolonging their service lives. The entire propulsion system requires less maintenance.

Waterjets are more efficient at higher speeds, particularly in multiple drive installations such as catamarans. With no underwater appendages, there is no increase in hull resistance as speed increases or more drives are added. Efficient operation can also be achieved over a broader range of speeds compared to propellers. Waterjets cannot overload an engine due to excess boat weight, towing, or extreme seas because they operate independently of the body of water under a boat.

A fast vessel needs a relatively higher amount of power than a slow vessel, and waterjets can provide a relatively large amount of power despite their relatively small size. Conventional propulsors would require relatively large propeller diameters.

A clean hull design, free of appendages, delivers greater speed. Drag resistance increases significantly as ship speed increases. Therefore, the absence of appendages becomes increasingly important as ship speed requirements increase.

The Office of Naval Research (ONR) uses an experimental 130-foot-long craft called the Advanced Electric Ship Demonstrator (AESD) to test various waterjet-based propulsion configurations at the Navy's Acoustic Research Detachment at Lake Pend Oreille, Idaho. ONR engineers achieved improved efficiency and maneuverability with a smaller, lighter propulsion system while reducing noise at the same time. Named *Sea Jet* (see Figure 3), the craft is essentially a quarter-scale model of the DDG-1000 destroyer. It has been used to test an AWJ-21 underwater discharge waterjet from Rolls-Royce Naval Marine, Inc., to validate better propulsive efficiency, reduced acoustic signature, less drag, and better speed as well as improved maneuverability for future surface combatants by eliminating rudders, shafts, and propeller struts.

Figure 4. ***USS Freedom*** **(LCS 1) is the first US Navy Littoral Combat Ship in an entirely new class of Navy surface warships. The ship is designed for littoral, or close-to-shore, operations and to provide access and dominance in coastal-water areas. (Photo provided courtesy of Lockheed Martin)**

Sea Jet has also been employed to demonstrate the General Dynamics Electric Boat RIMJET propulsor, which is a podded system that features a permanent magnet motor to power a propeller in the rim, rather than the hub, of the pod. The system uses sea water for coolant, which eliminates the typical elaborate cooling system consisting of pumps, piping, and heat exchangers.

ONR has also developed an Advanced Hull Form Inshore Demonstrator (APHID) which is testing a complete electric podded propulsion system. The Rim-Driven Propulsor Pod (RPD) uses a Pulse-Width Modulated (PWM) motor drive system mounted on the Hybrid Small Waterplane Area Craft (HYSWAC). Called *Sea Flyer*, the HYSWAC is built from a modified Navy Surface Effect Ship and uses a Vericor TF-40 gas turbine prime mover. Sea Flyer features an underwater lifting body ship that combines the high-speed capabilities of a hydrofoil and the rough-water stability of a small waterplane area twin hull (SWATH), so it delivers higher speed and improved stability over comparably sized vessels.

Cost can be an initial disadvantage of waterjets. They are expensive to purchase and maintain. Waterjets are made from costly stainless steel, which is more expensive than other propulsors that are typically made from copper alloys. However, waterjet lifecycle costs are relatively lower. Waterjets are less prone to impact damage, and reduced engine stress results in less engine maintenance and longer engine life.

The Littoral Combat Ships (LCS) will employ waterjets. Waterjets were chosen for LCS to provide high speeds in shallow waters, where the LCS will operate to combat asymmetric anti-access threats in the littoral regions of the world. Two variants of LCS are being built. Lockheed Martin has delivered the *USS Freedom* (see Figure 4), a semi-planing monohull design built at Marinette Marine in Wisconsin. General Dynamics is building a trimaran, the *USS Independence*, at Austal USA in Mobile, Alabama. Both will have diesels and gas turbines, and both will employ waterjets. The General Dynamics LCS has four steering and reversing waterjets, while the Lockheed Martin LCS has two steering and reversing and two booster jets. Both ships displace about 3,000 tons and up to 4,000 tons fully loaded. This will make the two LCS combatants the largest naval waterjet-powered warships.

While the two versions have taken different naval architectural approaches to the mission, both "seaframes" will carry mission modules that can be reconfigured to adapt to each ship's combat mission assignment.

USS Freedom is powered by two Rolls-Royce MT30 36 MW gas turbines and two Fairbanks Morse Colt-Pielstick 16PA6B STC diesels. The seaframe is based on the Fincantieri-built, Donald Blount-designed high-speed yacht *Destriero*, which holds the record for the fastest transatlantic crossing (60 knots). The 378-foot *Freedom* has a steel hull with aluminum superstructure. The two 36 MW gas turbines and two diesel engines power four large Rolls-Royce Kamewa waterjets. Four Isotta Fraschini Model V1708 ship service diesel generator sets provide auxiliary power.

USS Independence, the slender stabilized trimaran monohull built by the General Dynamics team, has an overall length of 418 feet, maximum beam of 93 feet, and full load displacement of 2,637 tons. The seaframe is based on Austal's design for the Benchijigua Express passenger and car ferry. Two General Electric LM2500 22 MW gas turbines and two MTU 20V8000M90 9100 kW diesel engines are the prime movers, powering four large steering and reversing Wärtsilä-Lips 2 X LJ160E and 2 X LJ150E waterjets. With all propulsion flat out, the Wärtsilä-Lips waterjets together expel roughly 27,000 gallons of seawater per second exiting from the jet nozzles at a speed around 90 mph. The trimaran variant built by General Dynamics will also have a retractable azimuth thruster.

CONCLUSION

One design is not optimum for all situations. Cruise ships with large portions of their itineraries at low power benefit from electric drive. Fast ferries, which go to full throttle as soon as they clear the breakwater and remain at full throttle until they reach the next port, would be at a disadvantage with electric drive. There are advantages to a mechanical drive system. Mechanical drive systems are more efficient compared to electric drive systems in terms of their ability to transmit energy from the prime mover to the propulsor. For example, the mechanical drive is estimated to transmit approximately 98% of the energy from the prime mover output shaft to the propulsor. The electric drive is estimated to transmit between 91% and 93%.

ACKNOWLEDGEMENTS
The author would like to thank Mike Worley, Vice President of Naval Marine Programs for Rolls-Royce North America; Mike Collins, former Program Manager for Integrated Power Systems with Program Executive Office–Ships (PEO Ships); Read Tuddenham, General Electric's Manager of Integrated Propulsion Systems and New Applications; Michael Reed, Senior Vice President for Advanced Technology with General Atomics Group; Tony Kean of HamiltonJet, Christchurch, New Zealand; and Marit Holmlund-Sund of Wärtsilä in Vaasa, Finland, for their contributions to this article.

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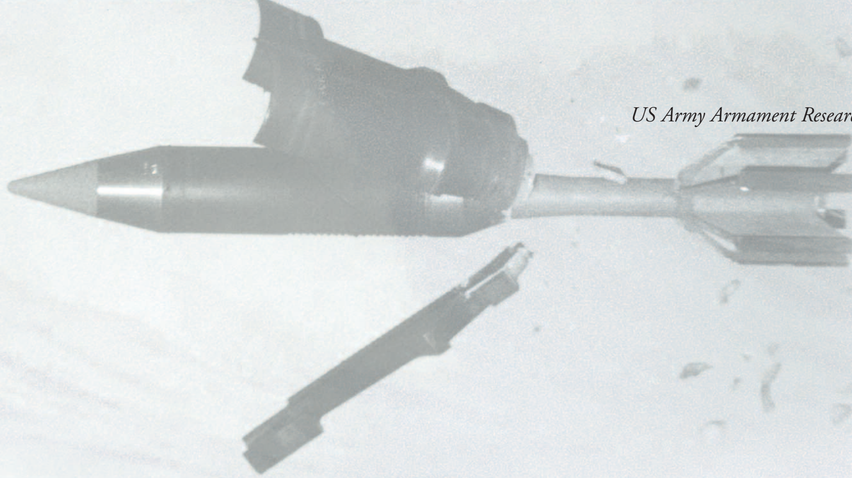
An Overview of Novel Power Sources for Advanced Munitions



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INTRODUCTION

Today's advanced gun-fired munitions, necessary for continuing operations and the Global War on Terrorism, require power sources with increased power and energy densities, all in a smaller package. Munitions power sources typically must operate over a wide temperature range (generally -45 to 145°F), withstand prolonged storage (10-20 years) prior to use, and survive the harsh environment of ballistic launch. Historically, thermal batteries have been used where high power was required for a relatively short time, and the munition rotated slowly, or not at all, as with rockets and missiles. Conversely, liquid electrolyte reserve batteries were better suited to the more moderately-powered, longer-lived electronic fuzes attached to rapidly rotating projectiles fired from the rifled barrels of large caliber artillery and some medium-caliber applications. This differentiation is due both to the capabilities of the electrochemical systems used in the respective application, and to the resulting differences in internal construction of the two battery types. Munition power sources are designed to be inert prior to deployment of the munition, which promotes long shelf life and enhances safety and reliability of the system. With the advent and continued proliferation of "smart" munitions, there is a need for power sources that have the best features of both thermals and liquid reserves: high power and high energy densities, with the ability to withstand high rates of spin. For some applications this may be realized with a hybrid approach, in which energy harvesters are used to supplement and/or substitute batteries as the munition power source. Regardless of their individual characteristics, the power sources should be as small as possible to maximize the lethality of the round, while also being safe, producible, reliable, and affordable.

US Army Armament Research Development & Engineering Center (ARDEC) has developed innovative power sources that offer a viable tactical solution for military applications and address the power lifecycle of smart munitions. Novel power sources for advanced munitions were developed at ARDEC under an Army Technology Objective (ATO) titled "Fuze and Power for Advanced Munitions".* This program addresses the development of power sources for artillery rounds, medium and small caliber munitions, missiles and rocket systems. The focus of ARDEC's efforts is to develop new energy sources, enhance the performance and capability of current power source components, and develop a systems approach to the management of power throughout the flight of munitions. This program was executed under the direction of ARDEC with the support from the Munitions Battery Team of the Army Research Laboratory (ARL) and a number of Small Business Innovative Research (SBIR) efforts.

The program execution is focused on developing technologies that define a munition's power system budget needs to address the mission profile for different munitions. To achieve this objective, the mission power profile has been identified as follows: (1) pre-launch power budget, (2) post-launch power budget and (3) flight power budget. The overall technical approach of this ATO program is to address those objectives that can be divided into three distinct areas:

- Improve thermal batteries by novel thermal management techniques that will result in longer lasting yet smaller batteries.
- Improve liquid reserve batteries with the development of catalyzed cathodes that provide higher power and energy densities plus new organic electrolytes that will lead to higher production throughput.
- Develop new types of energy harvesters to supplement and reduce the dependence on batteries (hybrid energy systems).

The program's mission is to develop advanced, affordable, onboard gun-fired munitions power sources technologies with increased energy and power densities, reduced volume and weight, increased mission time and improved extreme temperature performance. These technologies are broad-based and intended to be tailored for specific munition program applications. Successful incorporation of these technologies into existing and future programs is expected to increase lethality and enhance overall performance of smart munitions.

RESEARCH EFFORTS

A significant portion of this four year program focused on investigating, developing and maturing various power source technologies. Specific areas of research in support of the thermal battery enhancements and liquid reserve battery improvements were led by ARL's Munitions Battery Team. The thermal battery efforts conducted under this program were focused on demonstrating the feasibility and benefits of introducing new heat management techniques into existing thermal batteries. The liquid reserve battery efforts were organized into two research areas: catalyzed cathodes and organic electrolytes. The purpose of the catalyzed cathode research was to investigate the effects of metal macro-cyclic complex catalysts on the current density of an existing battery. The focus of the organic electrolyte research was to develop a more benign electrochemistry that may be suitable for lower power munition applications. A team at ARDEC led the investigation and demonstration of the Hybrid Energy Systems (HES) technologies. The work conducted under this program was focused on developing and demonstrating new types of energy harvesters that would use the forces naturally resident in a gun-launched munition's environment and convert that into electrical energy, supplementing or reducing the dependence on electrochemical devices. The development of HES technologies was leveraged with the use of SBIR contracts. The leading HES component demonstrated under this program was the piezoelectric generator. This generator uses a spring mechanism to store the mechanical energy harvested from setback acceleration and flight vibration and then delivers the stored energy to a customized piezoelectric element. Prototypes were delivered and assembled into instrumented carriers which were integrated into a gun-launched munition and subjected to ballistic testing at Aberdeen Proving Ground (APG) and Yuma Proving Ground (YPG). The ballistic tests were used to validate performance and survivability of power source components in harsh operational environments. The remaining sections highlight the main research, development and integration efforts that were accomplished under this ATO program.

Thermal Battery Novel Heat Management Techniques

Techniques to build thermal batteries with a longer lifetime or higher energy density are of paramount importance for the successful development and use of future smart munitions by the Army. The Low Cost Competent Munition (LCCM) thermal battery that had previously been developed at ARL was chosen as the benchmark. Efforts were focused on the effects and control of the internal operating gas atmosphere, optimal spatial distribution of heat source, and deployment of newer and better thermal insulation materials.[1] The investigation on the gas atmosphere was aimed at prolonging the lifetime of a thermal battery through

Figure 1. LCCM thermal battery prototypes.

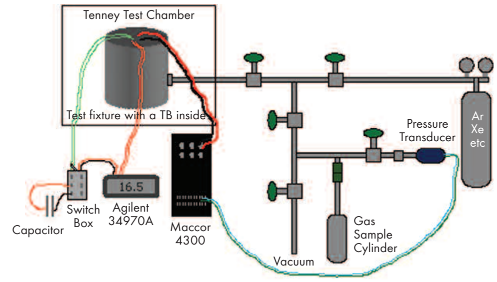

Figure 2. A schematic of ARL's testing system for thermal batteries.

the reduction of heat loss by eliminating the hydrogen component in the gas. This was carried out by evacuating a thermal battery during operation to demonstrate an extreme case of hydrogen elimination and by incorporating a gas getter in a battery for hydrogen reduction. The optimal spatial distribution of heat source materials was implemented by side- and end-wall heating with heat paper and heat pellets, respectively. The better thermal insulation was achieved by using thinner and more efficient thermal insulation materials in the battery.

The thermal battery components were made in a dry room from commercially purchased and in-house processed heat papers and cathode, anode, electrolyte, and pyrotechnic powders. The battery case of both the benchmark LCCM thermal battery and the improved versions measured 33.3 mm in diameter by 35.8 mm in height, exclusive of the external inertial igniter housing. The LCCM thermal batteries are shown in Figure 1. The thermal cell active stack was 19 mm in diameter with no center hole. For experimental work, ignition was accomplished by connecting a pre-charged capacitor with a piece of Nichrome wire buried in a heat paper pile, which in turn was connected with a heat paper fuse strip. For laboratory testing of the batteries, a heavy, sealable, and reusable steel test fixture was used to insure that the case temperature would remain near ambient temperature and closely approximate worst case heat sink conditions.[2] Figure 2 shows a schematic of the testing system for the thermal batteries. For this test, a Tenney Jr. Environmental Chamber was used to condition the test fixture at the test temperature of -40°C; a Maccor 4300 battery tester was used to apply the discharge load and record the voltage and pressure; an Agilent 34970A Data Acquisition/Switch Unit was used to monitor and record temperatures on the battery; a manual switch unit was used to initiate the battery and provide zero-time mark for other instruments, and a gas tubing manifold was used to monitor gas pressure, collect gas samples, and back-fill the battery with a selected gas when desired.

Prevention of rapid heat loss is a critical factor in prolonging operating lifetime as molten salt thermal batteries operate at temperatures as high as 600°C. For this reason, an operating gas atmosphere rich in a light element, such as hydrogen, is always to be avoided as has been demonstrated in our previous computational results.[3, 4] The experimental investigation of the effects of gas atmosphere in the lifetime of the LCCM battery was carried out by applying a vacuum of 7 Pa to a thermal battery during its operation and comparing the results with those of another battery without evacuation. The voltage profiles of the two, as shown in Figure 3b, demonstrate an increase in run-time for the evacuation condition (at cutoff voltage of 11 V) from 113 to 177 seconds, an improvement of almost 57%. Meanwhile, the internal resistance values, as plotted in Figure 3c, show that the application of evacuation had no effect on the internal resistances of the batteries. This

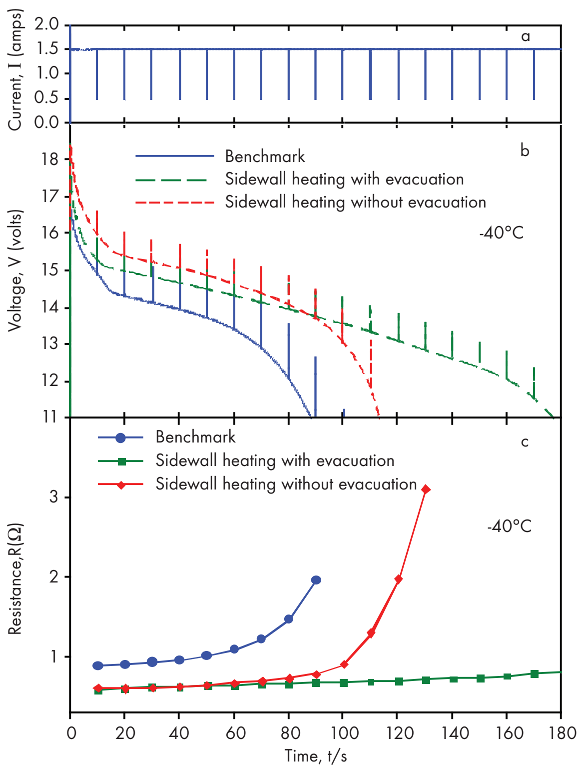

Figure 3. **Voltage-time (b) and resistance-time (c) curves at a loading current (a) for different thermal batteries tested at -40°C.**

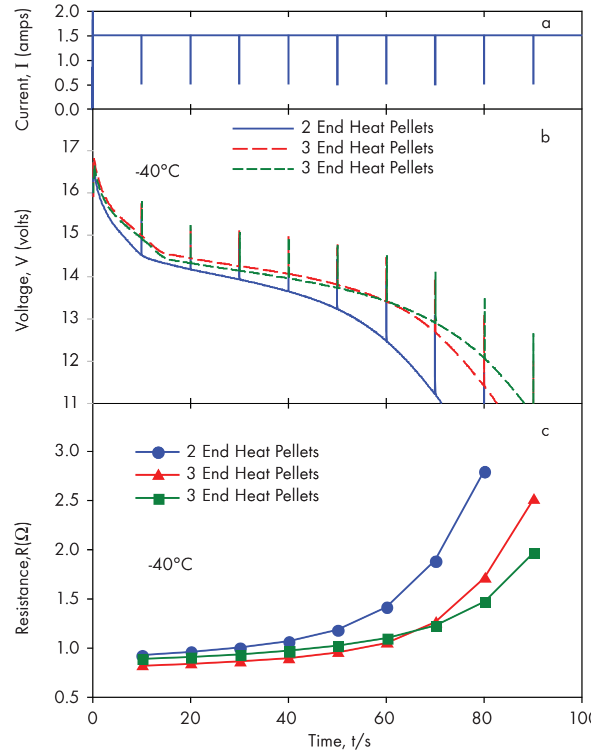

Figure 4. **Voltage-time (b) and resistance-time (c) curves at a loading current (a) for thermal batteries with varying numbers of end heat pellets.**

is to be expected as the internal resistance measures the collective resistance to the passage of electrons and ions in the battery through only solid phases. These internal resistance values were calculated from the curves in Figures 3a and 3b by the equation $R = \Delta V/\Delta I$, where ΔI is the drop of current in a current pulse shown in 3a, which in this case is 1 A, and ΔV is the corresponding jump in a voltage curve in 3b.

It is imperative that a sufficient amount of heat be provided in a thermal battery for proper operation. It is equally important that this heat source be spatially distributed in such a way that the heat generated can efficiently create a sustained uniform high temperature zone in the battery stack without local temperature spikes. In this sense, the traditional way of having pyrotechnic heat pellets stacked and interlaced with the thermal cells as the only source of heat supply is far from ideal. On one hand, it runs the risk of overheating the thermal cells while on the other hand it sets up very high temperature gradients both radially and axially causing rapid heat losses. One of the most effective and direct ways of remedying the situation is to add extra heat to the thermal insulation in the battery stack ends. Extra heat may also be placed in the insulation sidewall. This was attempted using different numbers of end heat pellets in benchmark thermal batteries to observe the effects and to obtain an optimal number of heat pellets.

Figure 4 shows the results of voltage profiles and resistance values for different numbers of end heat pellets. As shown in Figure 4b, the run-time of the batteries increases steadily with the increase in the number of heat pellets, up to four. The resistances change accordingly as shown in Figure 4c. A higher number of end heat pellets not only provides more heat for bringing the battery internals above the eutectic point of the electrolyte but also prevents rapid heat loss from the end thermal cells. The case of side-wall heating is demonstrated in Figure 3, between the curves of the benchmark battery and those of the battery without evacuation but with its side-wall heated by a layer of heat paper and with Microtherm as the thermal insulation material. The combined effects of side-wall heating and improved thermal insulation resulted in an increase in the lifetime of the battery from 88 to 113 seconds, an improvement of 28%, shown in Figure 3. Although it cannot be determined from the experiments so far just how much of the 28% is due to the side-wall heating alone, it is believed to be significant. For this purpose of heating the side-wall, research efforts have also focused on the investigation and experimentation with nano-layered bimetallic foils as the alternative materials, and found them to be very promising due to a unique and special set of properties. [5, 6]

High Rate and High Energy Oxyhalide Battery

In the last two decades, lithium-based batteries have become the predominant energy system for the electronic fuzes used in large caliber artillery applications. These batteries typically use lithium metal as the anode, thionyl chloride ($SOCl_2$) or sulfuryl chloride (SO_2Cl_2) as the electrolyte/liquid cathode (catholyte), and porous teflonated[†] carbon pads as the reaction site. For the sake of simplicity, these Teflonated carbon pads will be referred to as "cathodes" here because, at least structurally, they serve as the positive electrode in this system. The object of the research effort under this program was to significantly increase the power and energy capabilities of the current Multi-Option Fuze for Artillery (MOFA) battery simply by adding catalyst(s) to the cathode. The MOFA battery uses $SOCl_2$ as the catholyte, and was

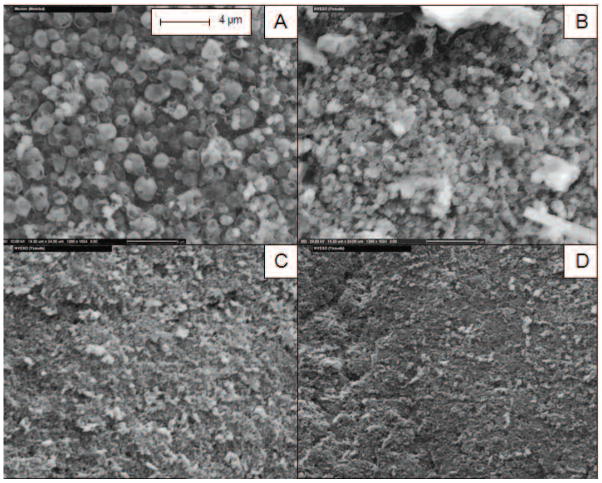

Figure 5. **SEM images of porous MOFA carbon cathodes, (A) containing 4.7% (w/w) total Co-SB and Co-TMPP, discharged at 75 mA/cm^2; (B) cathode without catalyst, discharged at 75 mA/cm^2; (C) 4.7% total catalyst, prior to discharge; and (D) cathode without catalyst, prior to discharge. All images are the same scale indicated in (A).**

Figure 6. **Enhanced liquid reserve MOFA battery prototypes.**

designed to operate at a current density of 35 mA/cm^2. Because of previously-demonstrated expertise in this area, PowerCell Technologies was tasked with this research and development effort, which was conducted primarily at ARL facilities.

At low-rate discharges (<5 mA/cm^2), the electrochemical reduction of $SOCl_2$ on porous teflonated carbon cathodes is not diffusion-limited, and the use of catalysts does not improve capacity. However, at higher rate discharges, the primary cause of cell failure in cathode-limited Li/$SOCl_2$ cells is the formation of a lithium chloride (LiCl) passivation film on the surface of the carbon cathode that creates a diffusion limitation. The use of metal macrocyclic complex catalysts, including metal phthalocyanines, metal phenylporphyrins, and metal quadridentate Schiff bases (MX), is believed to increase capacity due to the courser grain structure of the LiCl film, allowing extra porosity for continued penetration of $SOCl_2$ into the carbon cathode. Changes to the cathode surface, both before and following cell discharge, can be seen in Figure 5. These electrocatalysts also alter the mechanism of electrochemical reduction of $SOCl_2$, resulting in higher rate capabilities over non-catalyzed systems:

$$MX + SOCl_2 \rightarrow MX{\cdot}SOCl_2 \text{ (adduct)}$$
$$MX{\cdot}SOCl_2 + e^- \rightarrow (MX{\cdot}SOCl)^{\bullet} + Cl^-$$
$$(MX{\cdot}SOCl)^{\bullet} + e^- \rightarrow MX{\cdot}SO + Cl^- \text{ (fast)}$$
$$MX{\cdot}SO \rightarrow MX{\cdot}\tfrac{1}{2}(SO)_2$$
$$\tfrac{1}{2}(SO)_2 \rightarrow \tfrac{1}{2}\, SO_2 + \tfrac{1}{2}\, S$$
$$SOCl_2 + 2\,e^- \rightarrow 2\,Cl^- + \tfrac{1}{2}\, SO2 + \tfrac{1}{2}\, S$$

A combination of cobalt Schiff base (Co-SB) and cobalt tetramethoxyphenylporphyrin (Co-TMPP) was used as the catalyst in this study. Based on the results of lab cell testing, it was believed a current density of 75 mA/cm^2 could be achieved by adding the catalysts to the production cathode material, and incorporating this material into an otherwise unaltered production battery. Cathode material used in manufacturing the MOFA battery was obtained from EnerSys Advanced Systems, the battery's producer. The catalysts were impregnated into the base cathode material by dissolving them in an appropriate solvent, and then dipping the cathode material into the resulting solution. Prototype batteries were built at ARL, as shown in Figure 6, which use this material and then were tested against standard production batteries, which served as the controls. Significant increases in discharge life were observed throughout the typical operating temperature range of -45°F to 145°F. Finally, a length of cathode material was impregnated with catalysts at ARL and

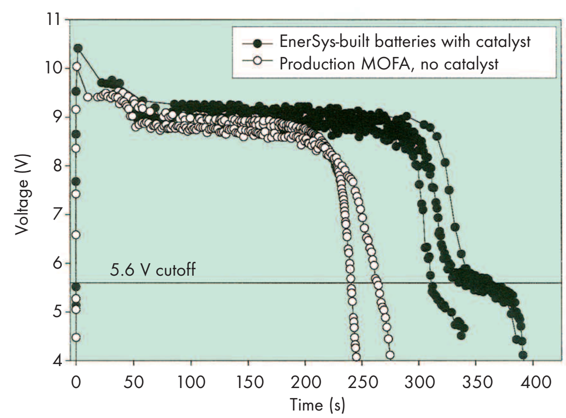

Figure 7. **Discharge performance of EnerSys-built batteries, with and without catalysts, at 75 mA/cm^2 and 70°F.**

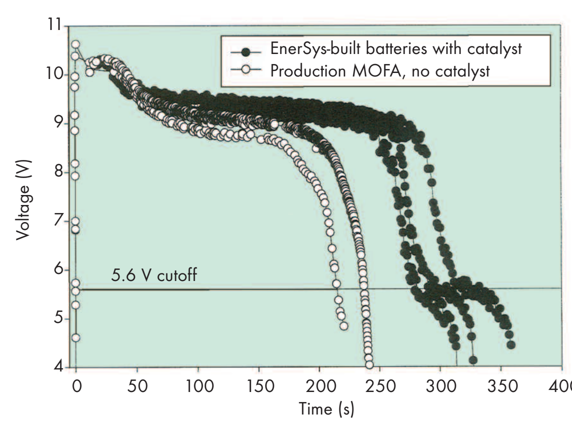

Figure 8. **Discharge performance of EnerSys-built batteries, with and without catalysts, at 75 mA/cm^2 and 145°F.**

then provided to EnerSys, where it was built into special engineering units using the MOFA battery production equipment. Because of some processing issues at ARL, this material only contained about half as much catalyst as intended, but the engineering batteries still performed significantly better than the controls at 70°F (Figure 7) and 145°F (Figure 8), and about the same at -45°F (Figure 9). However, earlier results (Figure 10) indicated that improved performance should also be possible at the low temperature extreme.

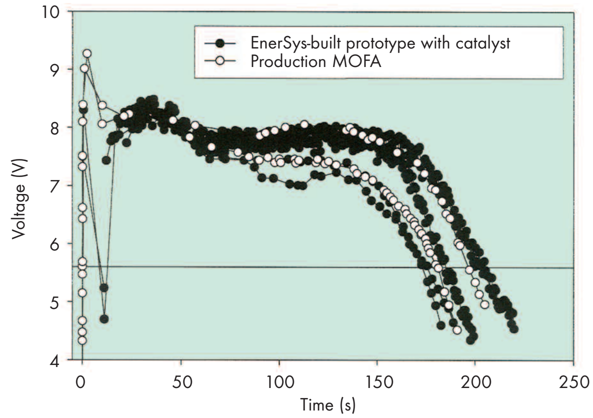

Figure 9. **Discharge performance of EnerSys-built batteries, with and without catalysts, at 75 mA/cm² and -45°F.**

Organic Electrolyte-Based Lithium Reserve Batteries

While $Li/SOCl_2$ and Li/SO_2Cl_2 batteries have proven themselves to be very capable, this electrochemical system can create significant design and manufacturing issues, as the catholytes are extremely hygroscopic and turn highly corrosive when exposed to moisture. Only a very few materials can withstand prolonged exposure even in the absence of moisture. Thus, material selection is limited and critical during the design phase. And since even the best dry rooms are not completely moisture-free, the manufacturing equipment that fills and seals the catholyte container is constantly being degraded by exposure and generally requires frequent maintenance. Finally, the combination of high vapor pressure and high ionic salt content typically found in catholyte formulations has caused fouling issues with dispensing equipment, particularly in the attempted manufacture of very small reserve batteries intended for use in submunitions and medium caliber applications. As a result, a research effort was launched to develop a more benign electrochemistry that also showed the potential for acceptable discharge performance over the typical Army operating temperature range of -45 to 145°F. The power requirement for this program was a relatively low current capability, about 5 mA/cm² at 3 volts, which were established as performance goals.

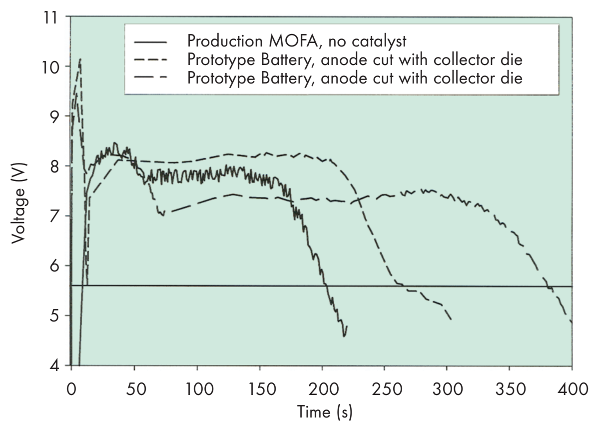

Figure 10. **Discharge performance of batteries, discharged at 75 mA/cm² and -45°F.**

MaxPower, Inc. was awarded a contract to select or develop an appropriate electrochemical system, demonstrate suitable performance, and conduct preliminary storage stability studies. Following an initial down-selection process based on existing literature and company experience, and focused experimentation performed under this program, MaxPower selected to investigate an electrochemical system that used lithium metal as the anode, the λ-form of MnO_2 as the cathode, and one molar LiBETI/EA (bisperfluoroethanesulfonimide in ethylene acetate) as the electrolyte. This electrochemical system has its basis in lithium-ion secondary battery technology, with a significant amount of existing data for some of the individual components. The selected electrochemistry has a working voltage of approximately 2.4-2.7 volts at the 5 mA/cm² rate, but since the batteries that would be built for demonstration would be of a series-cell design, that was acceptable. In fact, as with the catalyzed-cathode project, the MOFA application was used as a yardstick for the organic-electrolyte system due to the availability of production battery components and a highly-developed testing procedure. Discharge performance of the selected organic electrolyte system versus the MOFA requirement (pro-rated) is shown in Figure 11.

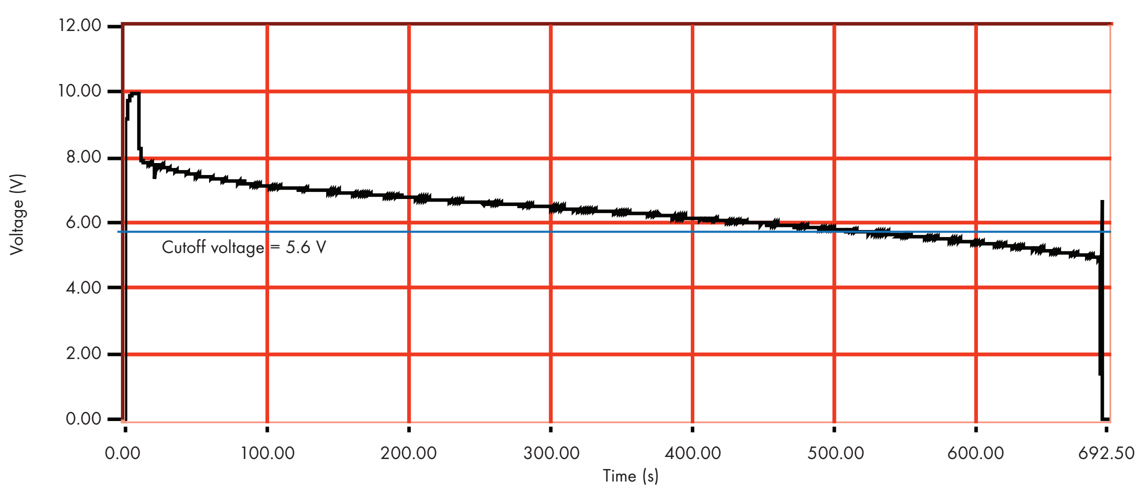

Figure 11. **Discharge performance of the organic-electrolyte system at 4.5 mA/cm² and 70°F.**

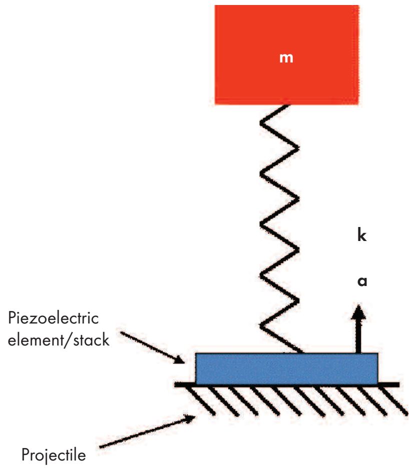

Figure 12. **Piezoelectric basic concept.**

The battery activates under a light (1000 ohms) load, and then at ten seconds into the discharge, a load equating to a 4.5 mA/cm^2 current density is switched in for the remainder of the discharge. In reality, a medium- to high-rate battery like MOFA would not be an ideal application for the organic-electrolyte system because of the organic system's significantly lower rate capability. However, low-rate applications do exist, and it is believed that the more-benign chemistry of the organic system will make it desirable in those situations.

To date, there have been limited efforts conducted to demonstrate long (10-20 year) shelf life for the organic system as a complete package. However, during down-selection of the electrochemical cell components, primarily the cathode, a significant amount of existing data and theory was reviewed to initially select candidate materials. The candidates were then subjected to variations in formulation, processing, and evaluation in an effort to gain further insight into their stability. Materials that showed the greatest promise were stored at elevated temperatures for up to six months, and then tested in laboratory cells against fresh materials. Those samples that showed any significant degradation in performance were dropped from consideration. Some of the candidate materials have been used in rechargeable battery applications, so there is some history with them. How well they apply to the uniqueness of the reserve battery application remains to be investigated.

Hybrid Energy Systems – Piezoelectric Energy Harvesters

The continuous stacked piezoelectric energy harvester as shown in Figure 12, consists of a mass and spring configuration designed to be in resonance at a frequency of oscillation $f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$. [7] The mass, m, is attached to a moving platform by a spring. The frequency of oscillation is controlled by the spring constant, k, and the value of the mass. If the moving platform is accelerated upward by an acceleration, a, as encountered during setback acceleration during gun launch, then the spring will compress a distance, d, required to balance the force generated by the accelerating mass. As a result, a potential energy PE = (½) kd^2 is stored in the compressed spring.

Once the projectile exits the gun barrel, the mass-spring system begins to vibrate, generating a recurring load on the piezoelectric element. The stored potential energy PE can then be harvested by extracting the charge generated on the piezoelectric element by the recurring load. During the flight, movement of the projectile due to forces resulting from ballistic environment would also result in the vibration of the mass spring system and mechanical energy could be harvested by the piezoelectric element. The test results have shown that efficiencies up to 33% in converting the available mechanical energy to electrical energy (including the power collection and regulation electronics) can be achieved.

The energy resulting from vibration is stored on the mass-spring combination and delivered to the stacked piezoelectric crystal as the mechanical system reaches resonance. An important component of this system is the Belleville washer that preloads the stacked piezoelectric crystal to prevent breakage under stress. The Belleville washer will ensure there is always a compressive force on the piezoelectric crystal. Without the washer, the harsh environments typically encountered during gun launch and flight may damage the piezoelectric energy harvester.

The methods used to harvest electrical energy for the axial design, as shown in Figure 13, are very similar to the radial design, as shown in Figure 14. The main difference is that each device would be tuned to the acceleration profile expected during the flight of the projectile (axial acceleration vs. radial acceleration). Another important distinction of this novel continuous piezoelectric energy harvester application is the use of a stacked

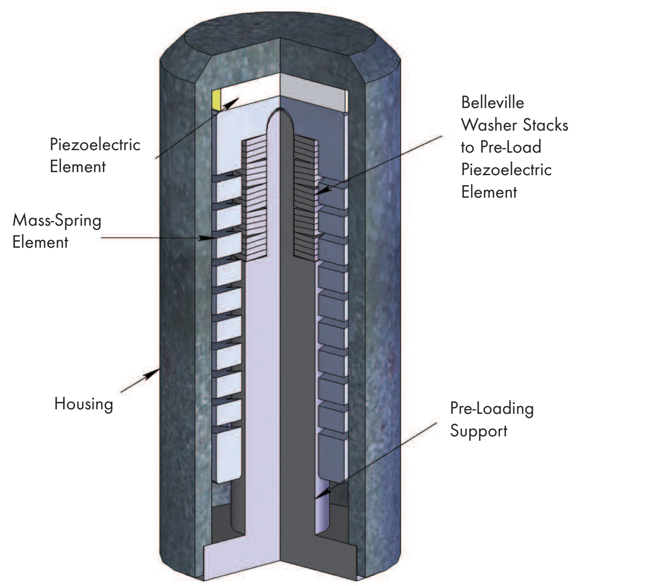

Figure 13. **Axial piezoelectric energy harvester.**

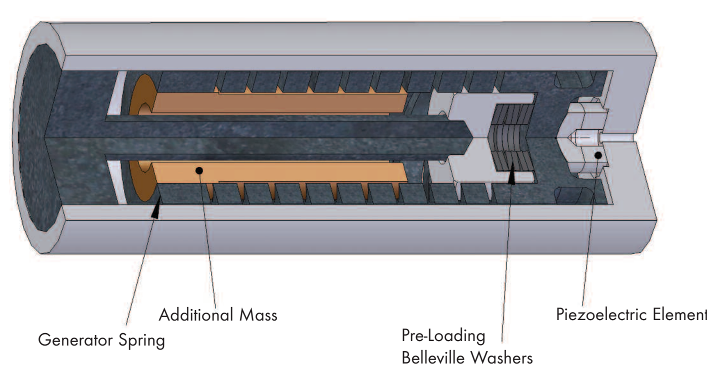

Figure 14. **Radial piezoelectric harvester.**

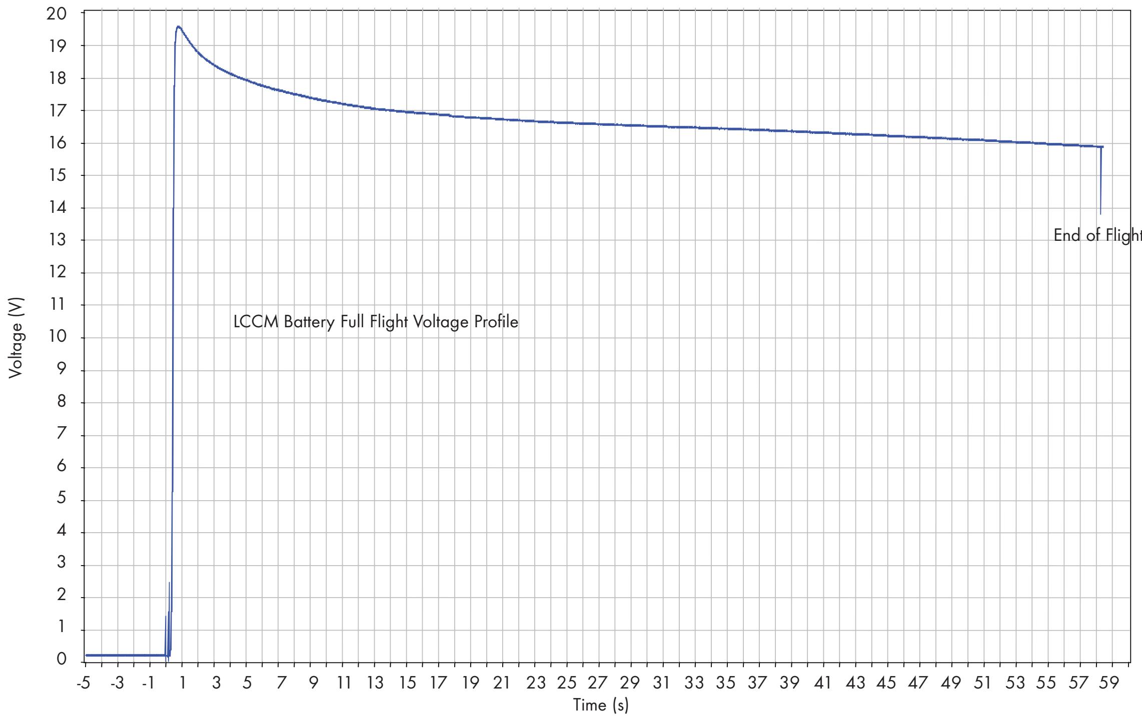

Figure 15. **Results of flight testing improved LCCM thermal battery prototype at YPG (10 ohm load).**

piezoelectric material that is comprised of multiples layers. Typically in piezoelectric applications, others have attempted to use single layer piezoelectric crystal devices to harvest energy. However, single layer devices will provide a response to mechanical vibration that is larger in amplitude but narrower in duration. This is not a implementation as a higher voltage in a shorter time is more difficult to regulate and not as efficient in harvesting energy of the pulse. For this reason stacked piezoelectric crystals will perform superior to a single piezoelectric layer by providing smaller amplitudes of voltage and lasting for much longer periods of time.

BALLISTIC TEST RESULTS

Flight tests consisted of packaging the power sources into gun-launched munitions for nominal tactical demonstrations. The power source prototypes were monitored with a telemetry system

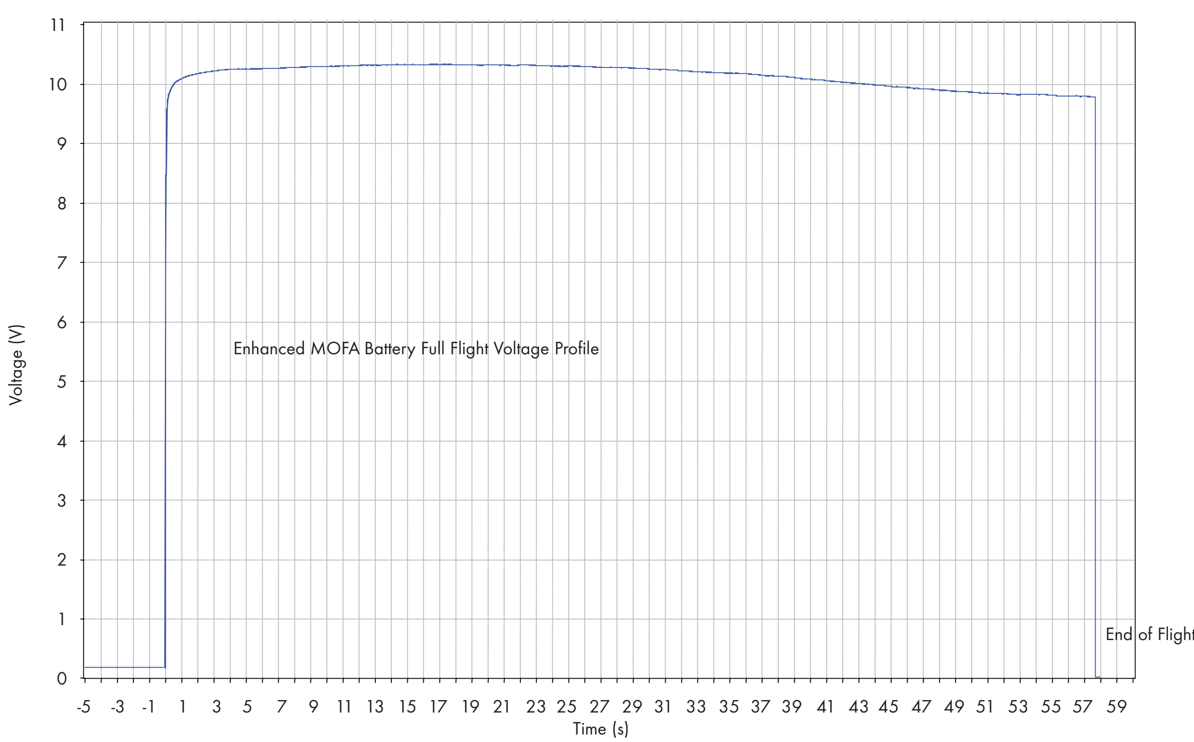

Figure 16. **Results of flight testing-enhanced catalyzed liquid reserve MOFA battery prototype at YPG (12.66 ohm load).**

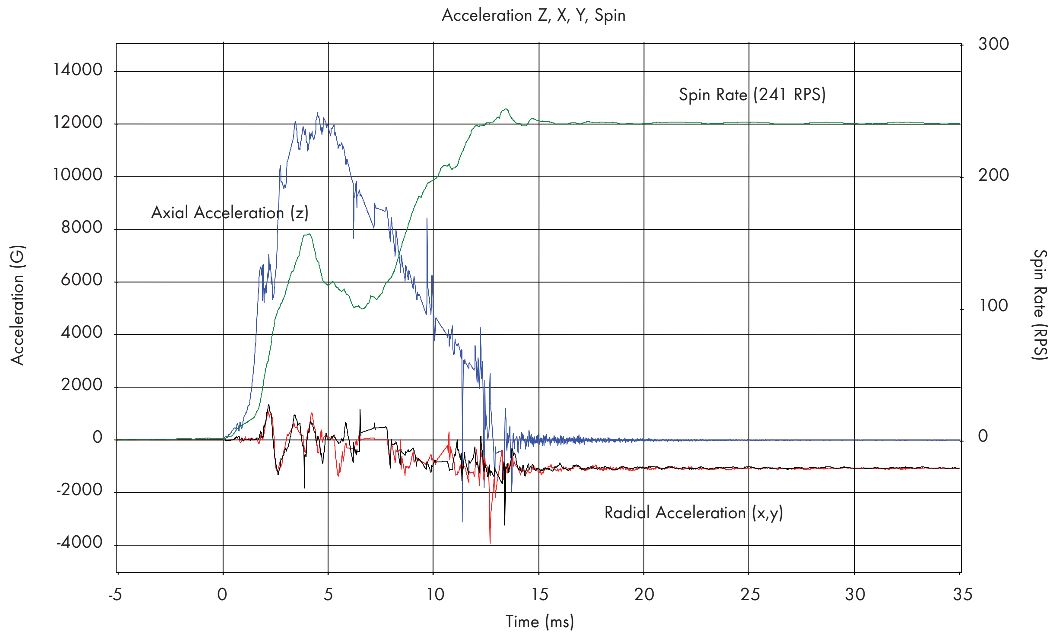

Figure 17. **Typical acceleration and spin profile of M549 projectile.**

via 'telemetry carriers', which allowed monitoring of component performance during testing, and the ability to record the data for analysis. The flight test validated a Technical Readiness Level (TRL) 7 (at a component level) for each component that demonstrated a successful test.

Prototypes of the enhanced thermal batteries, improved liquid reserve batteries (catalyzed cathodes) and hybrid energy systems (piezoelectric generators), were delivered, integrated on the M830A1 tank round and the M549 artillery round. They were then tested at APG or YPG, with results shown in Figures 15 and 16.

As shown, the improved LCCM thermal battery prototypes operated significantly longer than the benchmark batteries, consistent with the laboratory results achieving 30% increase in run-time and 30% increase in energy density. The enhanced MOFA liquid reserve catalyzed battery prototypes discharged at slightly higher voltages with an increased power density and increased run-time. The performance of the improved thermal and liquid reserve battery prototypes surpassed the program exit criteria. These prototypes survived the launch conditions with regard to acceleration (12,000-14,000 G) and high spin rate (average 240RPS), as shown in Figure 17, thereby successfully reaching TRL level 7.

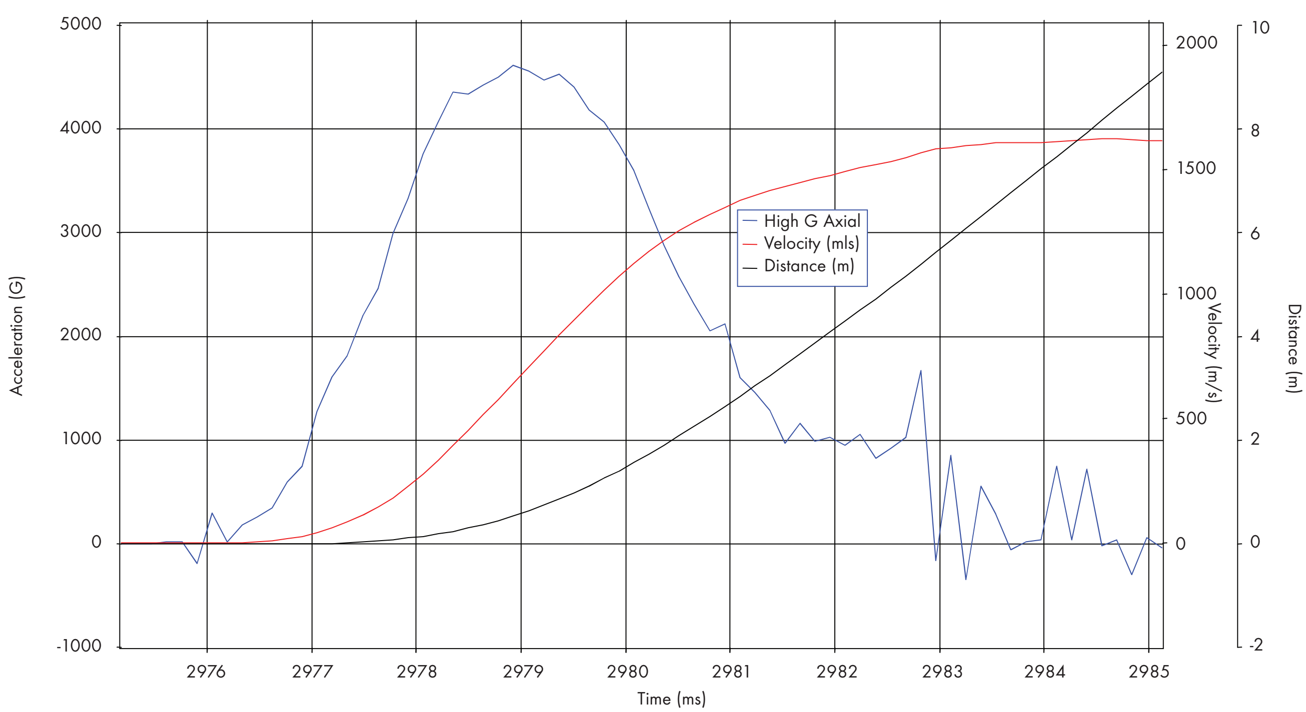

Figure 18. **Typical acceleration plot of M830A1 tank round.**

The piezoelectric generators produced 23 mW of electrical power harvested from axial and radial acceleration which successfully achieved the program requirement of 20 mW of power. The future design of piezoelectric energy harvesters can be optimized enabling additional energy to be harvested by matching the resonant frequency of the mass spring system to that of the munition. Additionally, the piezoelectric generators survived the high acceleration forces (45,000 G) encountered during gun-launch. Typical acceleration plots of the setback environment can be found in Figure 18.

SUMMARY

The technologies evaluated and integrated under this program achieved the overall program objectives of increased performance, energy density and increased power density, improved temperature performance, as well as the development of new energy harvesting devices that use the ballistic environment to generate electrical energy. The robust packaging and configurations of the thermal battery improvements, liquid reserve battery enhancements and energy harvesters have withstood the harsh environments encountered during gun launch on tank rounds and artillery rounds. These technologies are broad based and intended for use in any gun launched munition by tailoring the configurations to meet specific program requirements. Additionally, the investigation and laboratory demonstration of the organic electrolyte shows that the chemistry is less corrosive than the typical oxyhalide chemistries that are typically used. This represents a viable alternative to the more common oxyhalide chemistries for less demanding power applications. The technologies developed from this program will produce a positive impact to the warfighter, enabling safe, affordable, reliable and decisive military superiority. The test results validate that these technologies will help the warfighter safely meet their operational objectives by greatly enhancing lethality.

ACKNOWLEDGEMENTS

This project was made possible by the collaboration and teamwork between US Army ARDEC and ARL; the contractual relationships between ARL and PowerCell Technologies, ARL and MaxPower, Inc., as well as US Army ARDEC and Omnitek Partners, LLC.

A special acknowledgement goes to Dr. Michael Ding and Mr. Jeff Swank of ARL for their contributions to this article as well as Mr. Richard Dratler and Mr. Chuck McMullan for their contributions to the Power Sources ATO Closeout Report.[7]

The authors gratefully acknowledge the support of US Army ARDEC's Telemetry Team led by Mr. Boris Flyash, Mr. Mauricio Guevara and Mr. Lam Vo; and senior advisors Mr. Chris Janow and Ms. Maria Allende of US Army ARDEC.

NOTES & REFERENCES

* D.LE.2006.01

† Teflonation is a process involving mixing aqueous colloidal Teflon® emulsion with a powdered material, adding methanol to coagulate the Teflon®, followed by cleaning and drying. Teflon® is a registered trademark of E. I. du Pont de Nemours and Company Corporation.

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Mr. Richard Dratler received his mechanical engineering training at the State University of New York at Buffalo. He has devoted more than twenty years to the battery industry, while gaining extensive technical knowledge in an array of professional positions that include Quality Assurance Test Manager, Senior Product Engineer, Manufacturing Engineering Manager and Director of Production and Engineering. In 1997 Mr. Dratler assumed the position of Director of Technology in an entrepreneurial venture which led to the successful startup of a new manufacturing and research company specializing in the production of lithium batteries. He was the catalyst for creating a fully functional and operational manufacturing facility, successfully achieving ISO 9001 compliance. Currently, Mr. Dratler serves as an engineer at ARDEC. He provides expert advice to the division on the design and fabrication of reserve batteries, and serves on related technical and planning committees including multiple production, research and development and material release programs. He has co-authored various technical papers and patents.

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Mr. Charles McMullan is a Research Engineer at ARDEC. He graduated with a BS in Electrical Engineering from Villanova University. His technical position with the Advanced Precision Concepts Branch at ARDEC has covered a wide variety of research topics and focuses in the area of munitions' power sources. He is intimately involved in the development of hybrid energy systems and has demonstrated leadership capabilities while leading teams under the programs "Thin Film Technology" and "Novel Power and Energy Systems." He also serves as the power source technical lead for an emerging precision munition program. He has an in-depth understanding of the typical issues encountered with munitions power systems. His expertise continues to expand through his experiences with conventional as well as modern technological solutions to the very unique challenges that are present in a majority of munitions.

Mr. Hai-Long Nguyen graduated from Lehigh University in 2001 and Stevens Institute of Technology in 2006 with BS and MS degrees, respectively, in Electrical Engineering. Mr. Nguyen joined ARDEC in 2001 as Project Engineer to test/demonstrate RFID technology for into the Modular Artillery Charge Systems for CRUSADER, to conduct tradeoff of lens in Semi-Active Laser and power selection in thermal battery for Precision Guided Mortar Munition, to identify alternative concepts/designs for sensor/seeker and Multi-Functional Radio Frequency radar tracker for "unguided" Active Protection Systems. During the past few years, Mr. Nguyen lead efforts to demonstrate hybrid energy systems under Army Technology Objectives at Aberdeen Proving Ground and to conduct RF propagation testing in near/far field of the Real-Time Direct Measurement Sensors for Full Angular Orientation and Position. Mr. Nguyen authored and co-authored several SBIR topics in the areas of power/energy, sensor, and actuation. He has also published technical papers in NDIA and SPIE journals and conference proceedings of the aforementioned areas. His most recent effort is ARDEC Project Officer to advance the research of electrolytic supercapacitor and high-voltage capacitor.

Mr. Carlos M. Pereira is a research scientist and leads the Advanced Precision Concepts Branch at ARDEC. He is pursuing his PhD in Electrical Engineering at the University of New York at Stony Brook. Mr. Pereira leads efforts in Real-Time Direct Measurement Sensors for Full Angular Orientation and Position, the development of Novel Components for High Bandwidth Actuation for bang-bang control of precision munitions, the development of alternative methods to power munitions using Hybrid Power Harvesting Methods and the packaging of Reserve Power Systems on a Chip. His most recent efforts are in the research of power switching technologies in Wide-Bandgap Semiconductor Materials to be used for solid state switching. On a systems level, Mr. Pereira is a resident expert in High-g Packaging of electronics. Mr. Pereira holds numerous patents in most of the aforementioned areas.

Dr. Michael S. Ding obtained a PhD in Materials Science and Engineering in 1993 from Arizona State University, with dissertation research focused on processes of ion diffusion in mixed ionic-electronic solid materials. He worked as a post-doctor at Arizona State University on preparing and studying ionically conducting glasses and ionic solutions before moving on to Northwestern University in 1995 as a research fellow to study polymer electrolyte materials and assemble and test Li-polymer electrolyte batteries. Dr. Ding joined Army Research Laboratory (ARL) in 1996 as a national research Council Associate to work on non-aqueous solvents, electrolytes, batteries, and capacitors. He became a permanent research scientist of ARL in 2000, Team Lead of the Munitions Battery Team in 2005, and Acting Branch Chief of the Electrochemistry Branch in 2007. Dr. Ding has authored and co-authored more than 30 technical papers on refereed journals on topics of electrolytes, solvents, batteries, diffusion, ceramics, and mathematics, presented dozens of invited, oral, and poster presentations on major national and international conferences, filed and obtained several patents as a co-inventor, and received several awards for technical excellence. He is also a member of the Electrochemical Society.

Mr. Frank Krieger graduated from the University of Washington in Seattle, Washington, in 1964 with a BS in Chemistry. He has taken graduate level courses in chemistry and numerous short courses in mathematics, finite element modeling, electrochemistry, powder processing, heat transfer, and other thermal battery related technologies. He designed and built the PS132 thermal battery for the semi-active laser guided fuze program in 1985 and doubled the lifetime of a contractor-built high spin (275 RPS) thermal battery for the 105 mm nuclear howitzer (XM745 fuze) in 1989. He developed the 5 kW (85 A) Manlos thermal battery and the 275 revolutions per second LCCM thermal battery which won an Army R&D Achievement award in 1995. He has authored or co-authored approximately 30 technical papers and two patents. He is presently using the LCCM thermal battery as a test vehicle for investigating the use of nanofoil heat sources and the removal of hydrogen gas from thermal batteries.

Mr. Jeff Swank graduated from the Pennsylvania State University in 1983, with a BS degree in Mechanical Engineering. He worked on the C-17 program at Douglas Aircraft Company in Long Beach, CA, for nearly four years, and then joined Army Research Laboratory in 1988. Mr. Swank has participated in the development and testing of a number of liquid-electrolyte reserve batteries for Army and Navy electronic fuzes for artillery. He aided in the development of the LCCM thermal battery for an auto-registration round; the battery development team won an Army R&D Achievement Award in 1995. Mr. Swank has participated in several multi-service panels charged with assessing the munitions battery industrial base, including a Department of Commerce study published in 2005. He is currently involved in the development of advanced liquid reserve battery technologies for future applications.

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Fuel Cell Vehicle Fleet and Hydrogen Infrastructure at Hickam Air Force Base

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INTRODUCTION

The US Air Force Advanced Power Technology Office (APTO) at Robins Air Force Base (AFB), Georgia, and the Hawaii Center for Advanced Transportation Technologies (HCATT) formed a partnership in 2001 to establish a National Demonstration Center at Hickam AFB in Honolulu, Hawaii. The Center's mission is to facilitate the demonstration and validation of the latest fuel-efficient and environmentally compliant technologies for use in ground vehicles, support equipment, Basic Expeditionary Airfield Resources (BEAR), and base infrastructure. This program supports APTO's goal of providing increased capabilities and benefits to the warfighter/customer, supporting the US Air Force Environmental and Energy Policy requirements, and reducing dependency on foreign energy sources with the insertion of Advanced Power Technology.

The Demonstration Center at Hickam is a leading activity in evaluating hydrogen as a transportation fuel. Acknowledging that fuel cells require much more development and that a hydrogen fueling infrastructure is virtually non-existent, the APTO/HCATT team set out to accelerate those developments and introduce the first fuel cell vehicles and hydrogen fueling station in both the Air Force and the state of Hawaii.

There are now four vehicles in a growing fleet of fuel cell powered vehicles operating at Hickam along with a modular, deployable hydrogen production and fueling station. This paper addresses the initial operation of the fuel cell vehicles and the supporting hydrogen infrastructure.

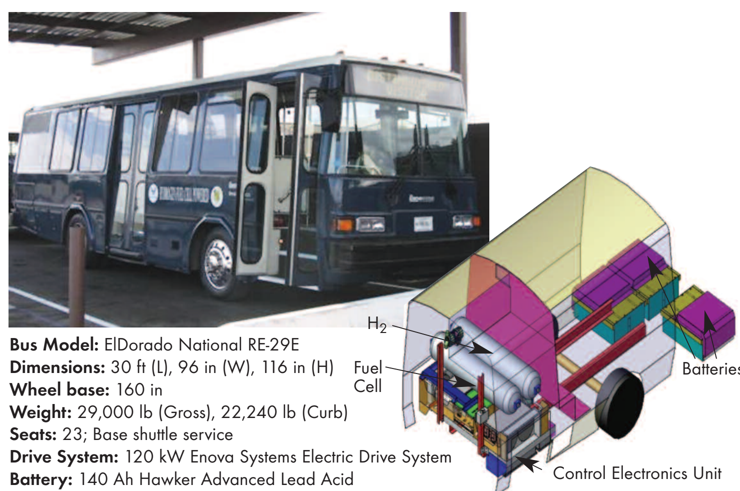
FUEL CELL VEHICLES

The four fuel cell vehicles include: a battery dominant, fuel cell hybrid electric 30 foot shuttle bus; a fuel cell hybrid electric step van; a fuel cell hybrid electric aircraft towing vehicle; and a new concept vehicle, which is a fuel cell augmented flightline maintenance support vehicle. Three vehicles use electric drive system components from the same manufacturer, and all four use fuel cells and hydrogen tanks from the same manufacturers. The commonality of components across various vehicle platforms demonstrates the potential for reductions in future acquisition costs.

Battery Dominant Fuel Cell Hybrid Bus

The first fuel cell vehicle, a 30 foot shuttle bus, was introduced at Hickam in February 2004. The 30 foot shuttle bus was selected to provide ample space for integrating the hybrid components. A small fuel cell was integrated with a large battery pack to minimize both technical and financial risks. Figure 1 identifies the components of the bus.

This shuttle bus was developed principally for operation on base, thus a range of 100 miles on full tanks of hydrogen and fully charged battery packs was considered sufficient. Battery-only range is 30 miles, to ensure the bus could continue to operate if the new technology fuel cell failed. Typically, the fuel cell keeps the battery packs charged; however, the bus is also grid connected and the batteries can be charged by plugging into a 220 volt



Bus Model: ElDorado National RE-29E
Dimensions: 30 ft (L), 96 in (W), 116 in (H)
Wheel base: 160 in
Weight: 29,000 lb (Gross), 22,240 lb (Curb)
Seats: 23; Base shuttle service
Drive System: 120 kW Enova Systems Electric Drive System
Battery: 140 Ah Hawker Advanced Lead Acid
Fuel Cell: 20 kW Hydrogenics Fuel Cell Power Module
Fuel Storage: 2 Dynetek 5 kg Hydrogen Storage Tanks (5000 psi); total storage – 10 kg

Figure 1. Battery dominant fuel cell hybrid bus.

About HCATT and the Partnership

HCATT is an element of the High Technology Development Corporation, an agency of the Hawaii state government. Since 1993, HCATT has managed several federally funded advanced transportation technology programs. Under this Air Force and state of Hawaii partnership there are three principal partners: APTO, HCATT, and the 15th Airlift Wing (15 AW) at Hickam AFB. APTO provides funding and program direction; HCATT, through contracts with private organizations, develops the technologies; and the 15 AW operates and evaluates the vehicles and equipment.

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(V) outlet using the onboard charger or plugging into an off-board, high-power fast charger.

Full operation of this bus using the fuel cell was initially delayed because of funding constraints resulting in a lack of hydrogen. Shortly after a hydrogen solution was achieved the bus was deployed for on-base distinguished visitors (DVs) transport. Hickam AFB welcomes a wealth of DVs, so this was considered an acceptable mission for performance evaluation. Bus duty cycles resemble that of urban driving.

One major problem surfaced early on. A drop in voltage occurred in one of the fuel cell stacks. The voltage irregularity was caused by a problem with the voltage sensor, not with the fuel cell stack itself. The problem was diagnosed and a solution identified. However, the fuel cell power module had to be removed from the vehicle and the stacks transported to the manufacturer for repair. An improvement in the production process solved the voltage sensing problem.

Typically, new technology vehicles undergo a one-year evaluation, but attempts are made to keep the vehicles in service as long as possible to provide a platform for further development and addition of technology improvements. As the first fuel cell vehicle under this program, this bus has experienced a few issues, some of which are a result of previously mentioned problems. It has recently had all the fuel cell stacks, the battery packs, and the control electronics unit (CEU) replaced. Following the replacement of the CEU, which involved the incorporation of new technology components, a communications problem with the fuel cell developed. This problem is currently being analyzed and, once resolved, the bus will be returned to service for further evaluation.

Fuel Cell Hybrid Step Van

The fuel cell step van was the second fuel cell vehicle introduced into the fuel cell vehicle fleet. The risk of developing a fuel cell dominant vehicle was much lower now because of lessons learned from the bus project. Major components of this van are identified in Figure 2. The van was only recently introduced to the base so limited performance data has been accumulated. This vehicle was developed principally for operation on base and it is designated for use by the maintenance squadron.

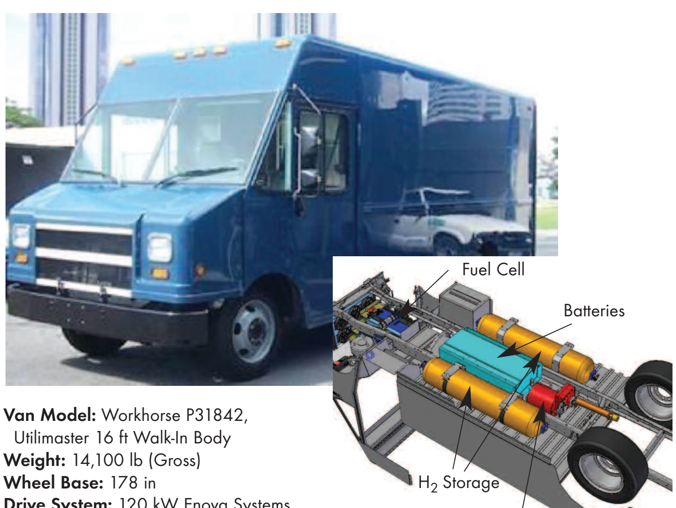
Initial diagnostic tests were run to ensure it met the performance specifications. Like the bus, the step van was configured to travel a minimum of 100 miles on base with full tanks of hydrogen. The tests demonstrated that this van has a 150-mile range (unloaded), not including the 42 ampere-hours (Ah) available from the battery pack. This van also features its own power generation capability, allowing maintenance personnel to plug their tools and equipment into 110 V or 220 V outlets (on board the vehicle) that are powered by the fuel cell.

Following a period of intermittent operation, performance degradation from the fuel cell power module in the van was observed; it was diagnosed and attributed to corrosion issues and crossover leaks. Essentially, aluminum oxide collected on the anodized endplate and anodized busbar in the manifold region of the fuel cell power module. To address this accelerated corrosion problem, the endplate and busbar were both redesigned to completely eliminate any metallic contact between the fuel cell process fluids and any stack components. Since implementing these changes, there has been no evidence of busbar or endplate corrosion in the manifold region.

The crossover leak was the result of a failed humidification device, which humidifies the hydrogen gas stream before it enters the fuel cell stack. There is a mixing of hydrogen and air in this device, and a crossover leak that develops within the humidifier can lead to a combustible gas mixture entering the fuel cell stack. This humidification device has been eliminated in the new technology fuel cell power modules. The metal ion contamination from the corrosion and the gas crossover leaks resulted in rapid degradation of the fuel cell membranes. Currently, the fuel cell stacks in this vehicle are being replaced.

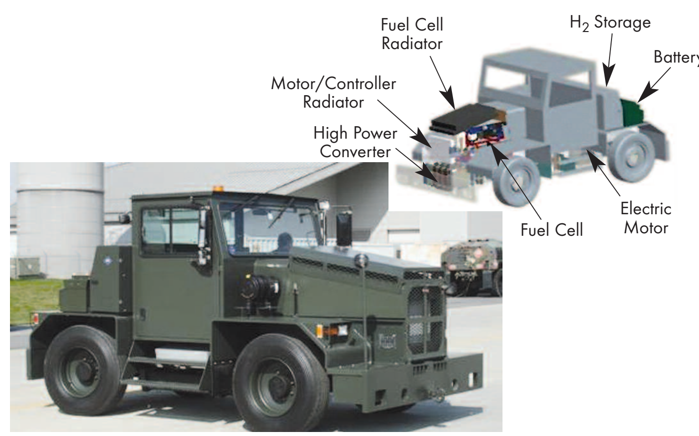
Fuel Cell Hybrid MB-4 Aircraft Towing Vehicle

The third fuel cell powered vehicle introduced to the fleet at Hickam AFB is an MB-4 aircraft towing vehicle. This vehicle utilizes the same fuel cell and electric drive system that were installed in the step van. The major components of the MB-4 are identified in Figure 3. This vehicle is operated by the Hawaii Air



Van Model: Workhorse P31842, Utilimaster 16 ft Walk-In Body
Weight: 14,100 lb (Gross)
Wheel Base: 178 in
Drive System: 120 kW Enova Systems Electric Drive System
Fuel Cell: 65 kW Hydrogenics Fuel Cell Power Module
Battery: 42 Ah Hawker Advanced Lead Acid
Fuel Storage: 2 Dynetek 5 kg Hydrogen Storage Tanks (5000 psi); total storage – 10 kg

Figure 2. Fuel cell hybrid step van.



Model: Entwhistle MB-4 Aircraft Tow Vehicle
Description: 14,000 lb Drawbar Pull, Four Wheel Drive; Four Wheel Steer
Curb Weight: 19,800 lb (stock)
Drive System: 120 kW Enova Systems Electric Drive System
Fuel Cell: 65 kW Hydrogenics Fuel Cell Power Module
Battery: 70 Ahr Hawker Advanced Lead Acid
Fuel Storage: 3 Dynetek Hydrogen Storage Tanks (5000psi); total storage – 7 kg

Figure 3. Fuel cell hybrid MB-4 aircraft towing vehicle.

National Guard Unit at Hickam AFB to tow F-15 fighter aircraft.

Initial operational testing is underway at Hickam. Early on, a major problem surfaced with the cooling system for the fuel cell power module. During operation the fuel cell would shut down prematurely due to an excessive increase in temperature. Using only 20 kW of power from the 65 kW fuel cell power module, the fuel cell shut down after about 42 minutes of operation. Initial diagnosis indicated the cooling components were not performing according to specifications. This was due in part to space constraints for installation of all the components of the hybrid drive system.

The fuel cell fan control system was improved to optimize the airflow, and a newly manufactured cowl above the radiator and engine compartment was installed to allow adequate air flow into the system. Additionally, a water circulation problem was detected. The system is circulating 20 standard liters per minute of water less than the specification required for the 65 kW fuel cell power module. Given that the batteries are the primary source for motive power and the fuel cell provides range extension, it was determined that 65 kW of output power was unnecessary for this configuration. The fuel cell was reset to operate at a maximum output of 30 kW. The 30 kW output of the fuel cell maintains the battery level while under continuous load, and the operating temperature is maintained well below the shut down temperature. Evaluation of the vehicle is ongoing.

Fuel Cell Augmented Flightline Maintenance Support Vehicle

The most recent fuel cell vehicle introduced is a new concept vehicle to support aircraft maintenance operations at remote sites. The project plan called for an all-electric drive platform complimented by a zero-emission generator to support maintenance on the flightline or at remote sites with no power, in keeping with the requirement for energy independence and the preference for zero-emission operations. An all-electric drive Ford Ranger pick-up truck was selected, but the bed was removed to facilitate installation of a newly designed utility bed. The new utility bed contains:

Model: Ford Ranger Electric Pick-up
Motor: 67 kW Siemens AC Induction Motor
Battery: 26 kWh Panasonic NiMH Battery Pack
Fuel Cell: 12 kW Hydrogenics Fuel Cell Power Module (APU)
Fuel Storage: 1 Dynetek Hydrogen Storage Tank (5000 psi); 1.8 kg
Equipment: 3 horsepower J-Air Compressor for Pneumatic Tools & Light Mast; 4 120 V (alternating current) Circuits, plus Retractable Extension Cord; 240 V AC Circuit; Pneumatic Light Mast Assembly

Figure 4. Flightline Maintenance Support Vehicle.

- A 12 kW fuel cell power module
- 1.8 kg of hydrogen compressed at 5000 psi
- A power bank consisting of four 120 V electrical outlets
- An additional retractable electric extension cord
- An air compressor for power tools with multiple coupling points including a 50 foot retractable air hose
- A removable pneumatic light mast with adjustable light module that can be extended by the air compressor
- A 220 V outlet for the light set, and an operator interface display to identify operations and faults

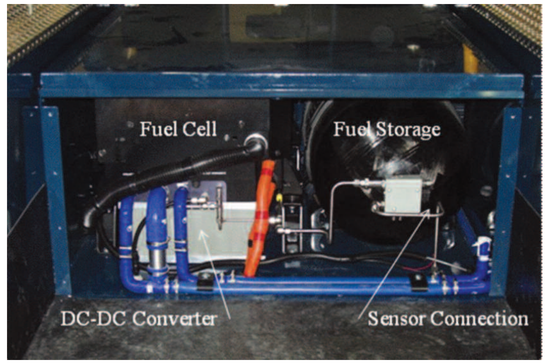


Figure 5. Fuel cell and hydrogen tank in utility bed; Operator Interface Panel in side compartment.

Figures 4 and 5 depict the major components of the Flightline Maintenance Support Vehicle. Evaluation of this concept vehicle has recently begun. All systems are operational and initial operator feedback is positive.

HYDROGEN INFRASTRUCTURE

The modular, deployable hydrogen production and fueling station is composed of Packaged Operating moDules (PODs), which are designed to be crush-proof, carbon steel packages for military or commercial transport. There are three primary PODs:

- Hydrogen Fuel Processor (H_2FP) using two Teledyne Energy Systems electrolyzers; production output 48 kg/day.
- Hydrogen Pressure Management (H_2PM) using a HydraFLX/Pinnacle intensifier to compress hydrogen up to 5000 psi.
- Hydrogen Pressure Storage (H_2PS) using nine Dynetek composite tanks; stores 50 kg of hydrogen at 5000 psi.

Two additional PODs provide power control and water for electrolysis; an MEP 9 generator is used to demonstrate deployment. Figures 6 and 7 show the installed station and its individual components. The deployable hydrogen fueling station serves as a model for other US Air Force installations and forward deployed bases.

The station began operating in November 2006. It was designed to accommodate fleet expansion, so the current demand for hydrogen on base is far less than the available output. Due to its deployable concept, the station was designed to be operated manually, and personnel on site operate the station and conduct vehicle refueling operations. A hydrogen fire safety and emergency response training course for base personnel was developed and made available for training throughout the Department of Defense.

The station at Hickam meets all applicable codes (fire, safety, electrical, etc.). It operates either from the electrical grid or the deployable MEP 9 generator. Connection to the power grid does not provide the most efficient means to produce hydrogen. However, the initial focus was to provide a safe and secure means of ultra-pure hydrogen production through electrolysis to meet the purity levels required for polymer electrolyte membrane (PEM) fuel cells while familiarizing military personnel with the use of hydrogen as a fuel and the handling of gas compressed at 5000 psi in vehicles. Two follow-on projects have already been

Figure 6. **Hydrogen production and fueling station PODs at Hickam AFB.**

initiated to add a 146 kW photovoltaic array and five 10 kW vertical axis wind turbines adjacent to the station to demonstrate the production of renewable hydrogen.

This station will continue to serve as a model for other installations. In this capacity, upgrades will be added as the demonstration and evaluation continue. Early modifications include: an upgrade to the H_2PM POD; the addition of an automated dispenser; and since the electrolyzers also generate oxygen, the addition of oxygen collection, compression, and storage for other uses on base.

Figure 7. **Hydrogen production and fueling station installed at Hickam AFB.**

FUTURE PROJECTS

By integrating fuel cell hybrid drive systems into a variety of platforms, HCATT was able to evaluate and overcome space and weight challenges and verify that various vehicles can perform to specifications. The hydrogen production station serves as a model for other installations and a basis for follow-on projects.

The program at Hickam AFB will continue to expand with additional fuel cell vehicles and upgrades to the hydrogen station. As indicated previously, the station is capable of producing more hydrogen than the current demand to allow continuing expansion and evaluation of the fleet. Some of the future fuel cell projects planned for Hickam include: a fuel cell powered light cart using metal hydride storage technology for hydrogen, another fuel cell powered shuttle bus, a fuel cell powered flightline sweeper, a fuel cell powered R-12 refueler, and a stationary fuel cell to power one of the buildings adjacent to the hydrogen station.

ACKNOWLEDGEMENTS

The author would like to thank the APTO for their foresight and emphasis on seeking solutions to energy independence while maintaining focus on meeting the needs of the warfighter. The APTO has provided us the opportunity to participate in this hydrogen fuel cell vehicle and infrastructure technology initiative, which is leading the way for advanced power applications in ground vehicles and support equipment in the US Air Force.

The author would also like to recognize the efforts of all of those involved in this program, including the following contractors: Hydrogenics, fuel cell manufacturer; Enova Systems, the systems integrator for the hybrid bus and van; Concurrent Technologies Corporation (CTC), the systems integrator for the hybrid towing vehicle and designer/developer of the Flightline Maintenance Support Vehicle; and HydraFLX, the designer/developer of the hydrogen station. Finally, the author would like to acknowledge the 15th Airlift Wing for their enthusiastic use and evaluation of the new technology vehicles and equipment.

Mr. Thomas L. Quinn has been the Director of the Hawaii Center for Advanced Transportation Technologies (HCATT) since 1994. HCATT is a division of the High Technology Development Corporation, a state government agency. HCATT, which was formerly known as the Hawaii Electric Vehicle Demonstration Project, was established in 1993 to represent one of seven regional consortia participating in the Defense Advanced Research Projects Agency (DARPA) Electric and Hybrid Vehicle Technology Program. This consortium continued to develop advanced transportation technologies under the follow-on US Department of Transportation Advanced Vehicle Technologies Program. Currently, HCATT manages programs for the Air Force Advanced Power Technology Office, which has established a National Demonstration Center for Alternative Fueled Vehicles at Hickam Air Force Base. Prior to this position, he completed a career with the United States Army, which included assignments as the Research and Development Officer for the United States Pacific Command and as a Program Manager at DARPA. Tom received his undergraduate degree from Penn State University and a Master's Degree in Management from Central Michigan University.

New Materials Developments for Military High Power Electronics and Capacitors

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INTRODUCTION

The military is moving toward more electrical platforms. To effectively sustain US military superiority the Department of Defense continues to utilize the latest advances in state-of-the-art equipment. Invariably, these advanced systems continue to require an increase in energy and power density while maintaining safety, reliability, size and weight. Military platforms such as warships, tanks, and airplanes, continue to require higher power to enable electrical powered weapons and detection systems for both defensive and offensive missions. The need for more powerful detection systems, communication systems, and more demanding auxiliaries also contributes to the demand for reliable, efficient, and clean power and energy.

The Defense Advanced Research Projects Agency (DARPA) is currently funding the Wide Band Gap High Power Electronics Program and the Integrated High Energy Density Capacitor Program. The success of these programs depends upon the ability to integrate new materials into high power electrical system components. Power electronics* and capacitors are two of the major components that make up all solid state power distribution systems. The objectives of DARPA's programs in these areas are to increase power and energy density through materials, processing, and packaging innovations. For high-powered, hydrocarbon-fueled platforms, these programs drive the development of materials that have higher efficiencies and performance capabilities for power electronics and passive devices. This article provides an overview of some of the efforts to enhance military high power electronics and capacitors through new and improved materials.

SEMICONDUCTOR MATERIALS FOR MILITARY HIGH POWER ELECTRONICS SYSTEMS

Solid state power electronics provides enhanced design flexibility and greater control of electrical power than analog systems. Increasingly, solid state silicon-based semiconductors are no longer able to meet the increased power demands of military platforms. Specifically, the need for higher voltages drives the complexity of silicon-based systems. A new class of semiconductor devices, based on silicon carbide (SiC), is now emerging into the market to meet the demands of the future military's high power converters, direct current (DC) distribution systems, electromagnetic guns, high energy lasers and propulsion systems.

Intrinsic Properties of SiC

Semiconductor materials are based on covalent bonds whereby the electrons in the outer shell are shared between host atoms. Elements in the upper rows on the Periodic Table have smaller atomic radii and stronger interatomic bond strength compared to those elements located in rows below these elements. The stronger covalent silicon-carbon bond in SiC results in a higher energy bandgap in the SiC semiconductor material, hence the name wide bandgap material. This bandgap is a fundamental characteristic of semiconductor materials because it is the energy needed to excite an electron from the conduction band into the conductive band. The three times higher band gap of SiC (3.28 electron-volts (eV) for 4H-SiC) compared to silicon (1.12 eV) results in a breakdown electric field in SiC that is ten times higher than that of silicon. This dramatically higher breakdown field in SiC, in turn, makes it possible to reduce the thickness of the drift region of a SiC power device by a factor of ten, resulting in a significantly reduced transit time for the carriers across the drift region of the device. This ultimately results in much faster switching and lower on-resistance for SiC power devices.

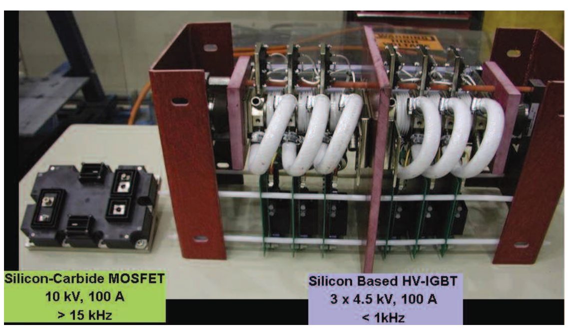

Figure 1. Comparison of size of silicon and silicon carbide converters courtesy of GE-GRC.

This higher breakdown field, coupled with the higher current densities that can be achieved in SiC power devices due to the higher thermal conductivity of SiC, means that it is feasible to replace silicon bipolar devices (e.g., Si insulated gate bipolar transistors (IGBTs) and PiN diodes) with SiC unipolar devices (e.g., SiC depletion mode metal-oxide semiconductor field-effect transistors (DMOSFETs) and Schottky diodes) in high voltage power electronics systems resulting in lower weight and volume as shown in Figure 1. SiC power devices have the added advantage of being capable of high temperature operation up to 225°C compared with the 125°C operating limit of silicon power devices. This not only significantly reduces the cooling requirements for SiC power devices, but also enhances their survivability in the event loss of cooling.

Material Development Status

Significant advances in the quality of SiC substrates and epitaxial layers have been made over the last decade. The catastrophic micro-pipe defects shown in Figure 2 have been reduced to an average of $<0.7/cm^2$ for 100 mm 4HN-SiC wafers as shown in Figure 3. There remains a need to reduce 1c screw dislocations to less than $100/cm^2$. At high voltage levels (10 kV) 1c screw dislocations cause unacceptable leakage current as shown in Figure 4.

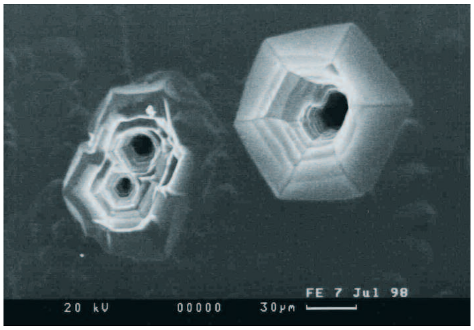

Figure 2. **Micro pipe defects. (Courtesy of CREE)**

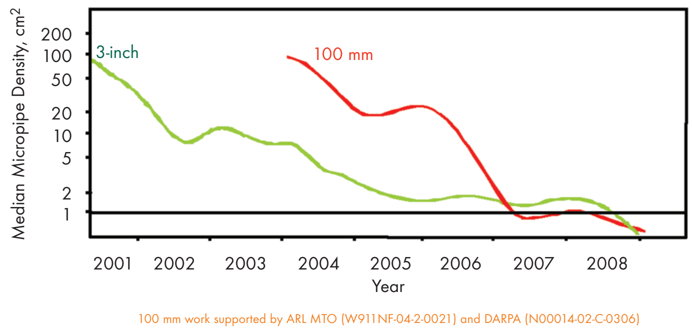

Figure 3. **Micro pipe defects in 100 mm SiC wafers.**

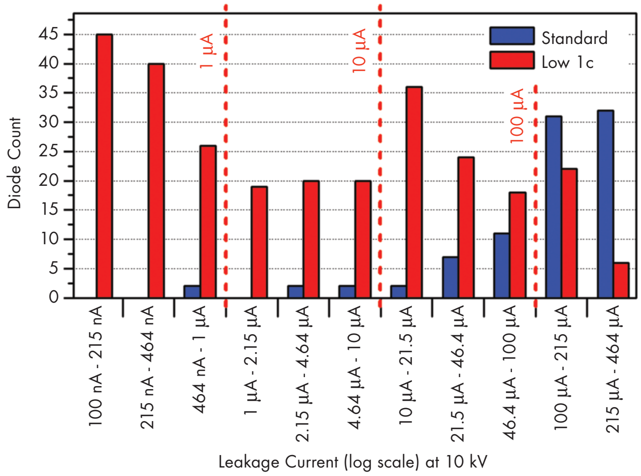

Figure 4. **Reduction of leakage current when low 1c dislocation (<200/cm^2) processes are used. (Courtesy of CREE)**

Basal Plane Defects are also present in SiC substrates but are handled through processing techniques to bend them to the outer edges of the boule†.

DIELECTRICS FOR CAPACITORS

To meet the high power demands for the future, improved passive electrical components are needed to keep pace with technical improvements in the state-of-the-art active power electronics. Today's capacitors take up to 50% of the volume of high power electrical systems and are a driving factor in thermal management overhead. Capacitor research today is attempting to provide energy dense capacitors beyond the capability of 1-2 J/cm^3 packaged to energy densities of up to 20 J/cm^3 packaged with high temperature capabilities (200°C), low losses (0.1% dielectric loss), and the ability for manufacturing scalability. A capacitor's performance is dependent upon the dielectric materials incorporated. To reach the 20 J/cm^3 packaged goal new dielectric materials will need to be developed in either polymer or ceramic materials with new processes and innovative configurations for higher packing density. Progress is being made towards a class of high power, high temperature capacitors that will enable future electronic weapons and pulsed power systems as well as more conventional high power distribution systems into smaller weight and volume.

Intrinsic Material Properties

The electrical energy stored in the electric field between the plate of an ideal capacitors (Figure 5) is in large part determined by two material parameters, permittivity and breakdown field strength, and can be given by equation 1.

$$U = \frac{\varepsilon\varepsilon_n E^2_{max}}{2} \qquad (1)$$

Where

U - energy density (J/ cm^3),
ε - relative material permittivity
ε_o - permittivity of free space (8.85418782 × 10^{-12} m^{-3} kg^{-1} s^4 A^2)
E_{max} (V/µm) - maximum field strength before material breakdown

Permittivity can be described as the ability of the material to polarize in response to an electric field through separation of ions, twisting permanent dipoles in the form of chemicals bonds, and perturbing electron orbitals. Greater polarizability results in higher permittivity. Dielectric breakdown strength can be described as the amount of electric field a material can handle before the electric field frees bound electrons. These electrons become accelerated and free other electrons through the material causing failure.

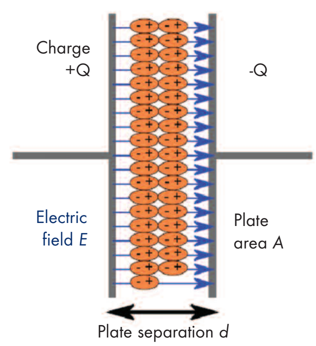

Figure 5. **Schematic of an ideal parallel plate capacitor. Charge separation within the parallel-plate causes an internal electric field. A dielectric inside reduces the field and increases the capacitance.**

Material Development Status

Currently, there are research initiatives to achieve high temperature, high energy density with long lifetime, fast discharge rate, high voltages, and low loss capacitor objectives through structural configurations of multiple materials. One example is the use of polymer extrusion technology to fabricate nanolayer structures of alternating polymer with different electrical properties. One polymer is chosen with high permittivity and the other possesses high breakdown strength. The resultant composite is an effective media with an overall increased energy density through the combined materials. Additionally, the multi-layered structure provides a barrier to the propagation of an electrical breakdown. Challenges include the ability to lay thin layers in a uniform manner over large areas and extrusion of high temperature polymers. Another approach toward high energy dense capacitor dielectrics uses a composite system of both polymer and ceramic dielectrics in an attempt to take the best properties of each and achieve a higher energy den-

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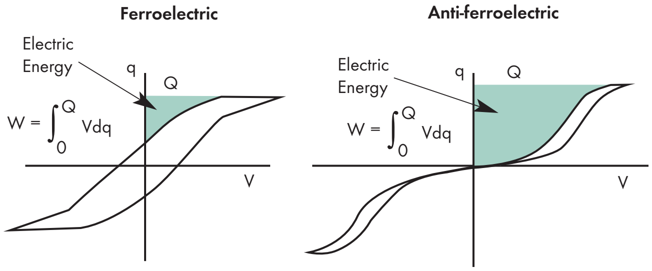

Figure 5. **Schematic depicting the increased energy density from ferroelectric to anti-ferroelectric behavior.**

sity. The polymer host provides the high breakdown strength while ceramic nanoparticles embedded within the polymer lend the high permittivity. There is also research using anti-ferroelectric nanoparticles to improve the energy density of dielectric materials (see Figure 5). As the electric field is increased, a phase change occurs within the material to enhance the permittivity in a nonlinear manner due to the polarization of the unaligned anti-ferroelectrics figure. The size of the anti-ferroelectric nanoparticle can be tailored to create an enhanced permittivity when high electric fields are applied. The challenges for embedding particles into polymers includes homogeneous dispersion as well as optimization of loading.

Lastly, research is currently underway to improve the energy density and reliability of ceramic capacitors. Ceramics inherently possess a high permittivity and high temperature capability. Current progress is focused on improving the breakdown strength and lowering the losses. It has been shown that ceramic material sintering parameters can be controlled to produce nano-grain ceramics. The ceramic grains on the order of 300 nm indeed provide increased breakdown strength and longer operating lifetime. Challenges for this system include control of material defects and impurities.

CONCLUSIONS

As silicon carbide reaches maturity, both in materials processing and in device manufacturing, it will become prolific in commercial and military high power applications. The advances in material processing have reduced the defects such that the higher yield has reduced cost and made it an attractive alternative for low power circuits in which power efficiency is highly valued (e.g., commercial laptops). Recent advances in the development and testing of high power modules are realizing the reduced size and weight that silicon carbide brings to the table. In the future, power applications that require efficiency and clean power more than 10 kW will routinely incorporate silicon carbide switches over silicon. Magnetic material improvements will also have the effect of allowing smaller, more capable systems in the future to meet the ever growing need for higher and more efficient power. The ability to integrate the active and passive electrical components into smarter, more modular circuits will change the way electrical systems are designed.

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* Power electronics involves the conversion and control of electrical power.

† Boule is a single crystal formed synthetically.

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An Introduction to Power and Energy

This article provides a brief overview of some of the most common sources of power and energy. It certainly is not comprehensive, but it does provide a solid background for many of the technical areas of power and energy presented in the other articles in this publication.

INTRODUCTION

Power and energy enable the use of the most advanced weapons, electronics, vehicles, and facilities available to the warfighter. Without consistent and reliable power and energy sources, the ability of the military to carry out their mission would be severely compromised. There are many ongoing efforts to develop new and enhance existing energy and power supply technologies, while reducing the consumption of energy. This article introduces a variety of sources of energy and covers some of the more common devices used to convert energy from one form to another.

Definitions

Basically defined, *energy* is a system's ability to perform work, and *power* is the rate at which energy is transferred to perform work. There are many forms of energy but all forms can be placed into one of two categories: kinetic and potential. Kinetic energy is simply the energy of motion. Potential energy is the energy stored by an object or system due to its position or state. Forms of kinetic energy include electrical, radiant, sound, motion and thermal energy. Forms of potential energy include chemical, gravitational, nuclear, and stored mechanical energy. A *fuel* is a substance that has stored energy which can be released deliberately to provide useful work or provide heat.

There are many sources of energy which are used to perform work on a system of any scale. For instance, on a molecular scale thermal energy can be used to form or destroy bonds between atoms and molecules. On a macroscopic scale, chemical energy stored in an energetic material, for example, can be used to propel a rocket away from the Earth's gravitational pull. Aside from the natural energy sources that sustain living organisms, various energy sources are harvested and used to power the function of artificial devices and processes.

ENERGY SOURCES AND FUELS

Energy behaves according to the First Law of Thermodynamics, also known as the law of conservation of energy, which can be formalized as:

> *Although energy assumes many forms, the total quantity of energy is constant, and when energy disappears in one form it appears simultaneously in other forms.*[1]

From this law it is clear that energy cannot be created, but rather converted from one form to another. Thus energy must be harvested from various sources.

Energy sources can be categorized in a variety of ways. Perhaps the most meaningful approach is to separate them into nonrenewable and renewable categories. *Nonrenewable energy* sources cannot be regenerated or replaced within a timescale that is sufficient to sustain their consumption. Thus, these energy sources will eventually become exhausted. Conversely, *renewable energy* sources can be replenished by natural processes at a rate that exceeds their consumption.

NONRENEWABLE ENERGY SOURCES

There are many fuel products that can be derived from nonrenewable energy sources. Even though by definition they are finite in quantity, nonrenewable energy sources are the most commonly used in part because they have very high energy densities that can be readily converted into useful work. Most common nonrenewable energy sources are derived from fossil fuels, however, radioactive materials provide nonrenewable nuclear energy.

Fossil Energy Sources and Fuels

Fossil fuels are derived from carbonaceous or hydrocarbon solids, liquids, and gases that have been formed from the decay of organisms contained within the Earth's crust that were exposed to heat and pressure over time. The most common fossil energy sources are petroleum, coal and natural gas.

Petroleum

Crude oil or petroleum is a natural, but nonrenewable fossil fuel primarily composed of a mixture hydrocarbons, including alkanes, cycloalkanes, and aromatic compounds. Nitrogen, sulfur, and oxygen are also present in the hydrocarbon compounds, and iron, nickel, copper and vanadium are also present in small amounts of the petroleum.

Petroleum is refined by fractional distillation process to convert the crude liquid to refinery gas, gasoline, kerosene, and diesel fuel. The liquids and solids remaining after distillation are lubricating oils, paraffin wax, asphalt and bitumen. The largest petroleum reserves are located in Saudi Arabia, Canada, Iran, Iraq, Kuwait, United Arab Emirates, Venezuela, Russia, Libya, Nigeria, United States, China, Qatar, and Mexico.

As the largest consumer of energy in the US, the DoD is also the largest consumer of petroleum products by using approximately 360 thousand barrels per day in 2007. This consumption cost approximately $11.5B. [2,3]

Gasoline

A common fuel derived from petroleum is a composition of aliphatic* compounds and enhanced with isooctane or benzene and toluene. Gasoline is a refined product of petroleum that contains a mixture of hydrocarbons having between 4 and 10

Table 1. Sample Composition of Gasoline.[4]

Component	Percent Composition by Volume
C_4 – C_8 Straight-Chain Paraffins†	15%
C_4 – C_{10} Branched Paraffins	25-40%
Naphthenes‡	10%
Aromatics§	<25%
Olefins**	10%

Table 2. Energy Density of Aviation Fuels.[5]

Aviation Fuel	Volumetric Energy Density (MJ/m^3)
Jet A	35,000
Jet A-1	35,000
JP-8	35,000
JP-9	39,573
JP-10	39,434

carbon atoms and other additives. The composition can vary significantly depending on environmental regulations which determine the blending requirements.

Like many fuels, gasoline releases its energy during combustion. For combustion to occur effectively, however, gasoline must readily mix with oxygen or air. Therefore an important property is its vapor pressure, which is dependent on temperature. Adjusting the butane (C_4H_{10}) content of the fuel can help control the vapor pressure. Under sufficient compression, gasoline can spontaneously combust without supplying a spark. This premature ignition or pre-detonation can damage internal combustion engines, however. The octane rating of gasoline refers to the mixture's propensity or resistance to pre-detonation. A higher octane rating indicates a greater resistance to pre-detonation.

Diesel

Diesel is another refinery product of petroleum. Diesel contains longer-chain hydrocarbons than gasoline, typically with 10 to 15 carbon atoms, and thus has a higher density. Diesel also has a higher energy density than gasoline.

Aviation Fuel

Aviation fuel is refined from petroleum and specially formulated to operate in aircraft or turbine engines on ground vehicles. Similar to gasoline and diesel, aviation fuels contain paraffins, olefins, naphthene, and aromatic hydrocarbons, as well as additives that impart chemical stability and other properties to the formulation. Important properties of aviation fuels include flash point, freezing point, energy density, density, stability (e.g., thermal, storage), volatility, lubricity, fluidity (e.g., viscosity), resistance to microbial growth, and inhibition of corrosion.[5] Aviation fuels are primarily based on kerosene, which is a mixture of hydrocarbons with 12 to 15 carbon atoms.

Jet A. The formulation known as Jet A is the standard commercial aviation fuel in the US. It is a kerosene-based fuel with a flash point†† of 38°C and a freezing point of -40°C.

Jet A-1. Jet A-1 aviation fuel is used by commercial airlines outside the US. Like Jet A fuel, Jet A-1 has a flash point 38°C, but it has a freezing point of -47°C.[5]

JP-5. Jet Propellant-5 (JP-5) is a kerosene-based jet fuel formulated to meet military specifications for certain properties. For instance, JP-5 has a higher flash point (minimum of 60°C) than commercial aviation fuels and a maximum freezing point of -46°C. The US Navy stores JP-5 aboard its aircraft carriers because of its relatively high flash point and low volatility, which makes it safer and less susceptible to ignition.

JP-8. JP-8 is a common kerosene-based military aviation fuel with a minimum flash point of 38°C and a maximum freezing point of -47°C.

JP-8+100. Based on JP-8, JP-8+100 has an additive package (consisting of a detergent, dispersant, metal deactivators and antioxidant) used to improve its thermal stability by 100°F.

JP-9 and JP-10. JP-9 and JP-10 are specialty fuels primarily for missile applications and are composed almost entirely of high-density naphthenes.[5] The JP-9 formulation is a blend of methylcyclohexane, perhydronorbornadiene dimer, and exotetrahydrodiclyclopentadiene.[5] The JP-10 formulation consists of a single hydrocarbon, exotetrahydrodiclyclopentadiene. The energy density for several aviation fuels is presented in Table 2.

Coal

Coal is an abundant, solid, nonrenewable fossil fuel that has been used as an energy resource for thousands of years. Explorers discovered coal in US in 1673, but commercial production (i.e., mining) did not begin until 1748 in Virginia.[6] There are several different types of coal, including lignite, sub-bituminous, bituminous, anthracite, and graphite.

Coal is commonly used as a fuel source for combustion to convert its stored energy to heat. This can be used as a simple heat source or to generate steam to drive a turbine and generate electricity.

Even though coal is found throughout the world, the US has the largest known coal resource. The coal reserves are spread across large areas of the country and it is mined in 27 states. The Department of Energy (DOE) estimates that 92% of the coal consumed in the US is used to generate electricity. The electricity generated from coal makes up approximately half of the electricity produced in the US. As of 2007, the US Army had seven

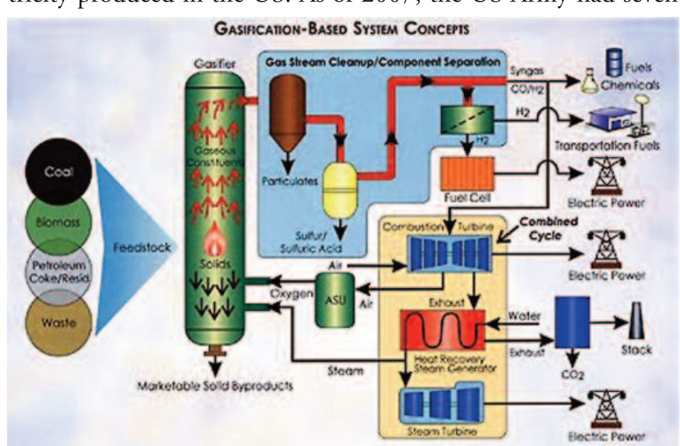

Figure 1. Coal Gasification Process.[8]

coal-fired power plants. These produced more than 7.6 million BTUs (British Thermal Units) of energy.[7]

Coal Gasification. Coal can be converted into other types of energy sources or fuels, such as synthetic fuel (see *Synthetic Fuel* below) and hydrogen, through a process that decomposes the solid into its base constituents in the presence of steam and oxygen under high temperature and pressure conditions (see Figure 1). The products of this gasification process are carbon monoxide, hydrogen and other gaseous compounds. During the process contaminants are separated and removed.

Coal Liquification (Coal-To-Liquid). Coal can be converted directly to a liquid or indirectly to a liquid through the gasification and Fischer-Tropsch processes.

Natural Gas

Natural gas is a naturally occurring, nonrenewable fossil fuel, and unrefined it is a mixture of gaseous hydrocarbons, primarily methane (CH_4). Natural gas can be collected from a variety of sources, including landfills and the anaerobic digestion of organic waste (i.e., decaying of biomass), but most commonly it is collected from crude oil and natural gas fields.

Natural gas is an abundant natural resource, especially in the US, and is therefore relatively affordable. Most natural gas deposits are a few thousand feet beneath the Earth's surface, but some can be more than 15,000 feet below the surface. Natural gas associated with crude oil can exist as a dissolved gas or free gas. Nonassociated natural gas exists in deposits absent of crude oil.

Methane hydrates are being studied as a possible alternative source of natural gas. Clathrate compounds are formed when water molecules bond in such a way as to encapsulate another molecule. A methane clathrates, also known as a methane hydrate, is an example of such a unique molecular structure that surrounds a methane molecule. These compounds have been found embedded in the ocean floor, sedimentary layers and in permafrost.

Properties. Natural gas is a colorless, odorless , non-poisonous, flammable substance. An odorant, typically butanethiol (also known as t-butyl mercaptan) or tetrahydrothiophene, is added in small amounts to aid the detection of natural gas leaks.

Table 3. **Typical Composition of Unrefined Natural Gas.[9]**

Methane	CH_4	70-90%
Ethane	C_2H_6	
Propane	C_3H_8	0-20%
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulfide	H_2S	0-5%
Rare gases	He, Ne, Xe	trace

Table 4. **Potential emissions reductions through the combustion of natural gas instead of gasoline.[14]**

Carbon monoxide (CO)	90-97%
Carbon dioxide (CO_2)	25%
Nitrogen oxides	35-60%
Hydrocarbons (non-methane)	50-75%

Prior to refining, the typical composition of natural gas is 70-90% methane, by volume, but also includes ethane, propane, butane and other alkanes (see Table 3). Other contents found in this fossil fuel include nitrogen, helium, carbon dioxide, water vapor and hydrogen sulfide. After refinement, commercial grade natural gas is almost entirely composed of methane.

Methane is in gaseous form at room temperature, condenses at -164°C, and freezes at -183°C. The density of methane is 0.67 kg/m3 at standard temperature and pressure (STP) compared to the density of dry air: 1.29 kg/m^3.[10,11] Methane is slightly soluble in water, for instance 3.5 ml of methane dissolves in 100 ml of water at 17°C. It is also soluble in alcohol, ether, and other organic solvents.[12]

Methane reacts with oxygen to produce carbon dioxide, water vapor and heat according to the following equation

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) + 890 \text{ kJ}$$

When fuel is mixed with air combustion occurs when natural gas concentration is between 5-15%.[12] The autoignition temperature of methane is 650°C.[12]

The products after combustion of natural gas are primarily carbon dioxide and water, whereas other fuels have a notable amount of additional byproducts. Therefore, natural gas results in a cleaner combustion than gasoline or diesel. Potential emissions reductions by using natural gas instead of gasoline have been estimated and are shown in Table 4.

In addition to reductions in these compounds, combustion of natural gas results in a reduction in carcinogenic pollutants and particulate matter compared to combustion of gasoline. Natural gas is considered to have an octane rating higher than gasoline.

Processing. Natural gas harvested from petroleum wells and other sources must be processed and refined to remove many of the unnecessary components and impurities to produce a commercial grade fuel. Alkanes other than methane are removed and collected for other uses.

Particulates, such as sand, are removed by scrubbers. In the case of natural gas dissolved in crude oil, it must be separated using a gravity separator, for example. Some water can be condensed out of the natural gas during refining, but dissolved water must be removed through absorption or adsorption.

Organic contents other than methane, such as ethane, propane, and butane are also extracted and subsequently separated as byproducts for other uses. Absorption is the method commonly used to extract the heavier organic compounds from the unrefined natural gas, while cryogenic expansion is used to extract compounds such as ethane which is close in

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molecular weight to methane. Separation of the hydrocarbons is then accomplished by fractionation methods.

Hydrogen sulfide is removed from unrefined natural gas by an absorption process. Amine compounds can be used to absorb hydrogen sulfide thereby extracting it from the natural gas stream. Elemental sulfur can subsequently be recovered for use in other applications.

Applications. As a combustible substance that can provide thermal energy, natural gas is commonly used for heating and cooking. However, there are several other applications of natural gas, such as fuel for vehicles and as a source of hydrogen for hydrogen production. In 2007, 29% of the nation's natural gas was used in industrial applications, 24% was used for residential heat and power, and 0.1% was used for transportation applications.[13]

Natural gas vehicles (NGVs) use compressed natural gas (CNG) or liquid natural gas (LNG). This is because if natural gas is used in its unpressurized, gaseous form a large volume is needed to power a vehicle for an acceptable distance. Even with CNG or LNG, NGVs have a more limited range than vehicles powered on conventional fuels. However, the power output of engines fueled by natural gas is comparable to those powered by conventional fuels. Natural gas vehicles can be powered by dedicated natural gas engines or bi-fuel engines which can run on either natural gas or a conventional fuel.[13]

Distribution. Small diameter pipelines are typically used to transport unrefined natural gas from the collection point to the processing plant or storage facility. The US has a network of interstate and intrastate pipelines which are used to transport natural gas from processing plants to the point of final distribution and consumption. Interstate pipelines are high pressure lines and are kept pressurized by compressing stations. Metering stations are also placed along the pipeline to monitor the natural gas in the line.

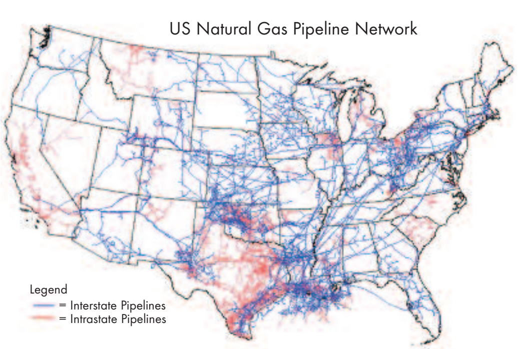

Figure 2. US natural gas pipeline network.[15]

Storage. Depleted gas reservoirs are used to store large volumes of natural gas underground. When a natural gas well becomes exhausted it can be used to store refined natural gas. In a similar way, underground salt caverns can be used to store natural gas. Natural water aquifers also can be reconditioned and used to store natural gas underground.

Synthetic Fuel

Synthetic fuel is technically defined as "a fuel that is artificially formulated and manufactured."[16] However, synthetic fuels are commonly described as liquid fuels derived from "coal, natural gas, or other solid carbon-containing feedstocks."[17] Synthetic fuels can also be extracted from oil shale and tar sands.[17]

History. Synthetic fuels were first made possible when the Fischer-Tropsch process was developed in the 1920s by Franz Fischer and Hans Tropsch. This process formulates hydrocarbon fuels from carbon monoxide (CO) and hydrogen gas (H_2), which allows carbon based products to be transformed into useful hydrocarbon fuel and lubricant products. The hydrocarbon product is formed when the reactants are passed through a catalyst under heat.

Advantages. During combustion synthetic fuels produce less carbon dioxide, particulate matter and sulfur compared to petroleum products refined from crude oil. This is because synthetic fuels are fabricated from "cleaner" reactants than crude oil-based petroleum products that are typically contaminated with nitrogen, sulfur, iron, nickel, copper, and vanadium. Good low temperature properties and excellent thermal stability are also noted as advantages of synthetic fuels.[16] Raw materials that are used as feedstocks for formulating synthetic fuels (e.g., coal and natural gas) are naturally occurring in US territory. Synthetic fuels that can be produced include gasoline, diesel, kerosene and various formulations of aviation/jet fuel. Synthetic fuels can also be used in existing engines and can be distributed using the existing infrastructure.

Disadvantages. Although the combustion of synthetic fuels produces less carbon dioxide than the combustion of fuels from petroleum products, the production of synthetic fuels results in high carbon emissions. The sulfur from petroleum-based fuels helps in the lubrication of moving engine parts. In addition, aromatic hydrocarbons, which are present in petroleum-based fuels, cause elastomeric seals to swell and therefore provide enhanced sealing capability. Finally, the mining of coal, which is one of the primary raw materials for synthetic fuels, is hazardous and can be environmentally damaging.

Department of Defense Use of Synthetic Fuels. The Air Force has been testing formulations of jet fuel that blends conventional jet fuel with the synthetic formulation. The Air Force has tested the synthetic fuel blend on several aircraft including the C-17 Globemaster III,[18] the B-1B Lancer,[19] the B-52 Stratofortress,[20] the F-15E Strike Eagle,[21] and the F-22 Raptor[22]. On March 19, 2008, the B-1B became the first Air Force aircraft to fly at supersonic speeds using the synthetic jet fuel blend. On August 19, 2008, the F-15E became the first Air Force fighter aircraft to fly using the synthetic fuel blend. The Army has been testing synthetic fuels for their vehicles as well. Performance and durability were evaluated with a synthetic fuel in the Caterpillar C7 engine.[23]

Nuclear Energy

Nuclear energy is the energy contained within the nucleus of an atom, specifically the energy that binds the nucleus together. Some of this energy can be released when nucleons (i.e., protons or neutrons) are split apart (fission) or fused together (fusion). Fission and fusion occur naturally. Radioactive materials are inherently unstable and decay over time by releasing packets of matter and/or energy. In some cases, the unstable nucleus of a radioactive material fissions and releases nucleons to achieve a more stable material. Fusion occurs naturally, for example, under the immense pressure and temperature of stars, such as the sun.

Although fusion reactions convert mass into enormous amounts of energy, only fission is currently a viable source of power for conventional applications.

Nuclear power is based on an abundant resource of energy, and generates electricity essentially by extracting energy from the atomic nucleus. Heat from the fission of atomic nuclei is used to create steam, which powers a turbine and ultimately converts the energy into electricity. However, since fission reactions in most stable matter do not readily occur (i.e., consume more energy than they produce), nuclear reactors use radioactive uranium or plutonium as fuel.

Nuclear power is known to produce electricity without the carbon emissions and other green house gas emissions associated with the use of petroleum and coal. However, it is the inherent danger associated with nuclear reactions as well as the challenge of handling and disposing of nuclear waste that has kept nuclear power from becoming the primary energy resource in the US.

At the end of 2007, there were 104 operational commercial nuclear reactors in the US.[24] However, nuclear power is not only limited to stationary facilities. The US Navy has ten aircraft carriers and more than sixty submarines powered by nuclear reactors.[25]

Nuclear Fission

Nuclear power is derived from nuclear fission reactions, in which a radioactive material is bombarded with matter to induce fission of the nuclei. As the nuclei fission, matter and energy are released. The ejected matter bombards other nuclei causing a chain reaction to occur. The energy is captured to be converted to useful work to ultimately generate electricity (see *Nuclear Power*).

Radioactive materials for conventional nuclear power are relatively rare and are considered nonrenewable. Uranium-235 (U-235) is a commonly used nuclear fuel and is extracted from uranium ore. The refining process involves the extraction of uranium oxide (U_3O_8) from the ore. Chemical processing refines the uranium oxide to uranium dioxide (UO_2) or metallic uranium. The enrichment of uranium refers to increasing the ratio of U-235 to uranium-238, a less radioactive isotope.

RENEWABLE ENERGY SOURCES

Renewable energy sources are drawing more attention globally because of their potential to reduce the reliance on nonrenewable sources including those that may be harmful to the environment. Natural resources that can be replenished on a time scale which can sustain their consumption are generally considered renewable. These energy sources typically include geothermal, wind, solar, biomass, and hydro. Each of these is discussed in some detail in the following sections.

Geothermal Energy

Geothermal energy is a renewable and abundant resource. The word geothermal refers to the thermal energy contained below the surface of the Earth. The center of the Earth is believed to have a temperature more than 11,000°F, which is approximately the temperature at the surface of the sun.[26,27] The Earth's thermal energy is derived from several natural processes.

A portion of the Earth's thermal energy remains from when the planet was originally formed by the condensation of hot gases and particles under gravitational forces. Additionally, as denser components were drawn to the center during the Earth's formation, the less dense materials were displaced toward the surface. This differentiation process involved friction, in which heat was generated, and some of the heat from this process was also retained. Moreover, latent heat is released from the core as it cools and expands in volume. Most of the Earth's heat, however, is derived from the isotopes of radioactive elements, such as plutonium, uranium and thorium, which are contained in the Earth's mantle and crust (see Figure 3). These radioactive materials release energy as they decay to become stable elements.[26]

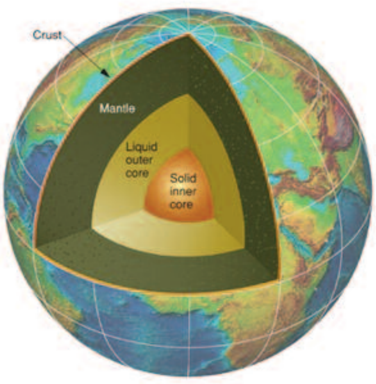

Figure 3. **Most of the Earth's heat is generated in the mantle and crust. (Graphic courtesy Lawrence Livermore National Laboratory)**

The thermal energy from the Earth is dispersed across the surface relatively uniformly, and temperatures increase as depth below the surface increases. However, there are geographical features which permit areas where higher subsurface temperatures can be more readily accessed. For instance, subsurface temperatures are higher near tectonic plate boundaries. Iceland has an advantage over other nations because the country is located where two tectonic plates meet. Other geographical features include volcanoes, hot springs and geysers. The Earth's thermal energy is a valuable resource, but the challenge is in how to capture and use it.

Direct Use of Geothermal Energy

Geothermal energy heats some natural bodies of water, such as underground reservoirs, which thus are considered *hydrothermal* sources of energy. Hot springs are natural springs that absorb geothermal energy. Hot water from these resources can be pumped directly into facilities to provide heat. Cities in Iceland utilize this inexpensive form of energy to heat entire districts.

Geothermal Electric Power

Electric power can be generated from hydrothermal resources. Hot water or steam is collected from hydrothermal resources within the earth. In some locations these resources are readily accessible, but other locations require drilling geothermal wells that are one to two miles deep. Geothermal steam can be used to

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drive turbines, thereby generating electricity. The majority of geothermal plants draw pressurized hot water from deep wells, convert it to steam, and use the steam to drive turbines, thereby generating electricity. These types of plants are geothermal flash steam plants. Other types of geothermal plants transfer heat from hydrothermal resources to another substance via heat exchange. US geothermal power plants are located in California, Nevada, Hawaii, and Utah.

Active and Passive Geothermal Systems

The temperature of the Earth's crust near the surface is relatively uniform regardless of geographic location or climate above the surface. The temperature generally ranges between 50-60°F. At depths of 15 feet temperatures fluctuations are 10°F or less.[28] These nearly constant temperatures can be used effectively as a natural heat exchanger to heat and cool facilities.

Active. In *active geothermal systems*, heat pumps circulate a fluid, usually water or a refrigerant, between a piping system buried in the earth and a building. The piping system exchanges heat to and from the earth depending on whether it is performing the function of cooling or heating. Basically, during warm seasons heat is absorbed from the building and dissipated into the earth for cooling, and during cool seasons heat is absorbed from the earth by the piping system fluid and is delivered to the building. These geothermal systems when used in conjunction with a well-insulated facility can serve as a highly efficient, low-cost method for providing heating and cooling.

Passive. The simplest use of geothermal energy is through passive geothermal systems. Similar to active systems a series of pipes containing a refrigerant, sometimes water, exchanges heat between the facility and the ground. The absence of a pump renders this a *passive geothermal system*. These systems have vertical pipes running from the foundation to several feet into the ground. Heat from the ground is drawn up into the building.

Advantages and Disadvantages

There are numerous advantages and few drawbacks of geothermal heating and cooling systems. In addition to geothermal energy being a renewable resource, advantages of systems that use it include low operating cost, low maintenance, and low or no emissions. The Environmental Protection Agency considers geothermal systems the "most energy-efficient, environmentally clean, and cost-effective systems for temperature control." The main drawback is the relatively high capital cost required to install the piping system, which may require borehole drilling. However, this cost can be recovered in a relatively short period of time through savings in conventional energy costs. In addition, supplemental heating and cooling systems may be required for facilities that are not well insulated or installations that are located in extreme climates.

Wind Energy

Wind power is a rapidly growing source of energy production in the US. Wind is an abundant, renewable, ultra-clean source of energy that can be harvested by wind turbines and converted to electricity. Although the power output of a single windmill is relatively small, wind farms can produce a substantial amount of energy.

The Earth is unevenly heated by the sun, which causes temperature differences and pressure gradients. Air flows as a result of pressure gradients and other forces. The kinetic energy of wind can be harnessed to drive mechanical devices which convert it into a useful energy to generate electricity.

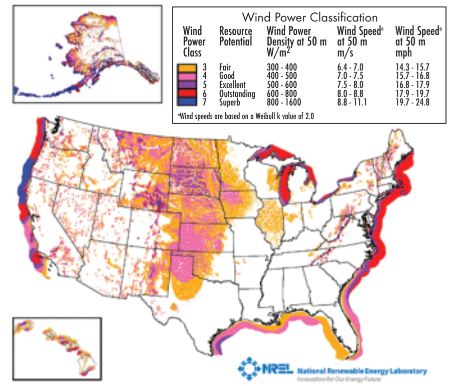

Figure 4. Wind distribution in the US.[29]

The energy of the wind has been harnessed by humans for thousands of years. Wind was used for marine vessel propulsion by the ancient Egyptians, and wind mills were built by the ancient Chinese to pump water and the ancient Persians to grind grains. Denmark is known for their use of wind mills to generate electricity, which began in the late 19th Century.

Since wind is naturally occurring and generated primarily because of the sun's energy it is a renewable resource. Wind energy is ultra clean because there is no combustion involved in the generation of electricity. Moreover, wind is an inexpensive and abundant domestic resource. It can be cost competitive with other conventional electricity generating methods. Wind farms and individual wind turbines can be built almost anywhere, including offshore.

One of the primary challenges with wind power is the irregular nature of wind, which results in the inconsistent generation of electricity. Energy storage devices can be used to enable a more consistent supply of electricity. Depending on the location and energy requirement, another challenge is the size and number of wind turbines needed to generate sufficient electricity.

Wind power density in the US ranges varies significantly across the nation (see Figure 4). The highest wind power density is typically found offshore, and at elevations of 50 m it can be in the range of 600 – 1600 W/m^2.[29]

Bioenergy

Bioenergy is renewable energy derived from biomass. Biomass is organic or biological matter that can be used for or converted to fuel. This generally includes matter from plants and animals, but excludes the organic matter that has been converted fossil fuel. Biomass, such as wood, has been used for millennia to produce heat, and other biomass, such as sugar cane, can be processed to produce ethanol for use as a biofuel.

Biofuels are predominantly synthetic fuels but have an important distinction due to the raw materials used to manufacture them. The feedstocks originate from biomass which includes agricultural crops (e.g., corn), wood, plants, grasses, agricultural waste, and other waste products.[30,31] Biomass is defined as "any organic matter that is available on a renewable or recurring basis."[31]

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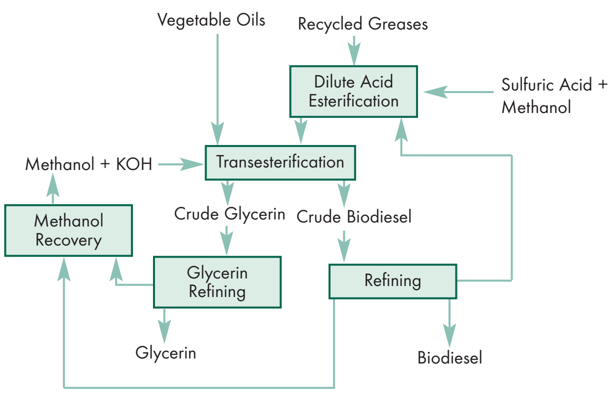

Figure 5. **Example of a biodiesel production process.[32]**

Ethanol and Other Alcohols

Sugar, which is extracted from plants and other biomass, can be decomposed through microbial fermentation to produce ethanol and carbon dioxide.[32] The sugar is extracted by milling, crushing, soaking, and chemically treating the feedstock. The ethanol produced by fermentation is distilled to purify and separate it from water.[33] Methanol, propanol, and butanol can be produced using a similar process.

Biodiesel

Biodiesel is primarily derived from soybean oil in the US, but vegetable oil, rapeseed oil, sunflower oil, palm oil, animal fats and algae can be processed to produce biodiesel. This is accomplished through transesterification of the feedstock, which produces biodiesel fuel as well as crude glycerin (see Figure 5). Crude glycerin, as a byproduct of the transesterification process, can be re-processed and used for a variety of other products. Mono-alkyl esters and long-chain fatty acids are the major constituents of biodiesel, but it can be blended with diesel derived from petroleum products. This synthetic blend has a lower sulfur content than conventional diesel, but unlike synthetic fuels the biodiesel composition has good lubricating qualities. Biodiesel also has a higher energy density than ethanol.

Biofuel Requirements for Use as Jet Fuel

Typical biofuels do not have an energy density sufficient to serve as a jet fuel. In order to be used as jet fuel, biofuels must be able to achieve the energy density levels of JP-8.[32] Even if the energy density meets this requirement, no engine modifications should have to be made in order to use a biofuel as jet fuel. Finally, jet-fuel grade biofuel must be able to be produced in quantities sufficient to meet demand, and must be transportable and stable enough for typical fuel storage.

Production of Jet Fuel from Algae

Algae can be cultivated to produce specific oils which can be processed into high energy density hydrocarbons. Micro-algae is of interest for jet fuel because it can be used to produce a higher ratio of fuel-grade oil quantity per land area than other biomass. For instance, micro-algae is capable of producing between 5,000 and 15,000 gallons of oil per acre per year, while rapeseed can only produce approximately 130 gallons of oil per acre per year.[32] Algae oils can be processed using the same hydroprocessing technologies currently used for refining conventional oils. This can produce a fuel similar to kerosene and the jet fuels traditionally derived from petroleum products.

Advantages

One advantage of biofuel is that it is renewable since the feedstocks are obtained through renewable resources. Biofuels are also potentially "carbon neutral". The carbon dioxide (CO_2) that is consumed during growth of the feedstock materials compensates for the CO_2 that is produced when the biofuel is combusted.[34] However, the production of biofuels requires energy, which thus causes additional CO_2 emissions, and therefore it is not entirely "carbon neutral".

Disadvantages

The primary disadvantage of biofuels is that they typically have a relatively low energy density compared to conventional fuels.[34] Ethanol also has a relatively low operating temperature.[34] Biodiesel freezes when temperatures near 0 °C and therefore limit its performance in cold weather climates.[32] Blending biodiesel with conventional diesel can alleviate this deficiency to a certain extent. Both biodiesel and ethanol have greater affinity for water than conventional petroleum products, which can have negative consequences including increased corrosion.

Solar Energy

The sun provides an abundant and renewable source of energy in the form of electromagnetic radiation. Some of the thermal energy, which is transferred from the sun to the Earth via radiation, enables other energy sources, such as wind and bioenergy. Solar energy can be used directly for heat, converted to electricity using the photoelectric effect, or by harnessing the thermal energy for driving steam turbines. More than 1.3 kW/m^2 of solar energy is incident on the Earth's atmosphere. While solar energy may be an abundant energy source, it varies significantly across regions (see Figure 6) and in many cases it also requires a significant amount of work to convert it into usable energy.

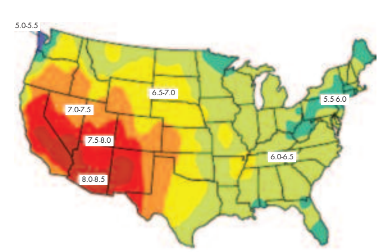

Figure 6. **Map of average solar radiation received across a horizontal surface in the month of June (units are kWh/m^2/day).[35]**

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Table 5. Physical and thermodynamic properties of hydrogen.[38,39,40,41]

Density†	0.08375 kg/m³	0.005229 lb/ft³
Specific volume†	11.94 m³/kg	191.3 ft³/lb
Viscosity†	8.813 x 10^{-5} g/cm-sec	5.922 x 10^{-6} lb/ft-sec
Specific heat (constant pressure)†	14.29 J/g-K	3.415 Btu/lb-°R
Specific heat (constant volume)†	10.16 J/g-K	2.428 Btu/lb-°R
Thermal conductivity†	0.1825 W/m-K	0.1054 Btu/ft-h-°R
Enthalpy†	3858.1 kJ/kg	1659.8 Btu/lb
Internal energy†‡	2648.3 kJ/kg	1139.3 Btu/lb
Autoignition temperature*	585ºC	1085°F
Flame temperature in air†	2045ºC	3713°F
Flammable range in air†	4.0 – 75.0 vol%	
Ignition energy in air	2 x 10^{-5} J	1.9 x 10^{-8} Btu
Higher heating value†	141.86 kJ/g	61,000 Btu/lb
Lower heating value†	119.93 kJ/g	51,500 Btu/lb

†At normal temperature and pressure = 20°C (68°F) and 1 atm

*The autoignition temperature depends on hydrogen concentration (minimum at stoichiometric combustion conditions), pressure, and even the surface characteristics of the vessel. Reported figures range from 932-1085°F.

‡Reference state: Internal Energy U=0 at 273.16 K for saturated liquid; Entropy S=0 at 273.16 K for saturated liquid.

Table 6. Volumetric and gravimetric energy density of hydrogen gas and liquid.[43]

	Volumetric Energy Density		Gravimetric Energy Density	
	MJ/m³	Btu/ft³	MJ/kg	Btu/lb
At 1 atm and 60°F (15°C)	10.1	270	120	51,700
At 3,000 psig and 60°F (15°C)	1,825	48,900	21,791	9,354,570
At 10,000 psig and 60°F (15°C)	4,500	121,000	53,730	23,147,300
Liquid	8,491	227,850	101,383	43,587,705

Hydroenergy

Hydro power can be defined as power derived from the potential and kinetic energy of water, and is therefore considered a renewable resource. Most commonly associated with the function of dams for generating hydroelectric power, hydro power is also generated by harnessing the energy of waves and tides.

Wave Power

Wave power is generated by harnessing the energy of surface waves or the pressure oscillations under the surface. This energy can be harvested using buoys, for example, that can convert the mechanical up and down motion into electricity. Wave power has had limited success, and is better suited to niche markets and regions proximal to wave energy rich resources, such as the Pacific Northwest.

Tidal Power

Tidal forces exerted on the Earth by the moon and, to a lesser extent, the sun cause the periodic rise and fall of ocean waters. This natural cycle is a source of energy that can be harvested and converted into useful power.

OTHER IMPORTANT SECONDARY ENERGY SOURCES‡‡

Hydrogen

Hydrogen in its elemental state, protium, is composed of a single proton and a single electron, while its isotopes deuterium and tritium contain an additional one and two neutrons, respectively. It is the most abundant element in the universe and is the lightest (i.e., smallest atomic mass). It is estimated that three quarters of the mass in the universe is composed of hydrogen atoms.[36] Hydrogen is very chemically reactive and readily combines with many other elements, particularly carbon and oxygen; on its own hydrogen is found in its relatively stable, diatomic gaseous form H2.[36]

Hydrogen gas, H_2, is highly flammable and when undergoing combustion (i.e., reaction with oxygen) it produces water and heat, as shown in the combustion equation:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) + 572\ \text{kJ}[37]$$

Since the only product is water and heat, hydrogen is a very clean burning fuel.

Hydrogen is not considered an energy source, but rather, an energy carrier like a spring, because it is not abundantly occurring on its own in nature and therefore must be produced from other compounds. Hydrogen can be produced by leveraging other renewable energy sources, such as wind, solar, and hydroelectric power, and therefore it can be supplied from a variety of geographical regions. Once produced, most commonly by steam methane reforming, hydrogen as a fuel can be used in internal combustion engines and fuel cells. Liquid hydrogen is also used as a propellant, and is well known for its use to launch the Space Shuttle. Selected physical and thermodynamic properties of hydrogen are given in Table 5.

Energy density is the amount of energy contained in matter per

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unit mass or unit volume, and is often used to compare different types of fuels. The mass-based energy density of hydrogen is very high but the volume-based energy density is low compared to other fuels. One pound of H_2 has 44.4% of the energy contained in one gallon of gasoline.[42] The energy densities of hydrogen gas and liquid at several pressures are given in Table 6.

Hydrogen Production

Hydrogen as a resource is mostly contained in water (H_2O) and organic matter (i.e., hydrocarbons), and therefore must be extracted to be useable as a fuel. The following are some of the common processes used for hydrogen production.

Steam Methane Reforming. About 95% of the hydrogen produced today in the United States is made via steam-methane reforming, a process in which high-temperature steam (700°C-1000°C) is used to produce hydrogen from a methane source, such as natural gas which is mostly methane gas. In steam-methane reforming, methane reacts with steam under 3-25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide.[44]

Electrolysis. Electrolysis involves decomposing water into its base components of hydrogen and oxygen. This is accomplished by applying an electrical current through water via electrodes.

Gasification. Hydrogen can be produced by other organic feedstocks, such as coal and biomass. Using high temperature and pressure to gasify coal or biomass, the gasified organic product is then converted to synthetic gas, which is then reacted with steam under temperature and pressure to produce hydrogen. Syngas is primarily carbon monoxide and hydrogen (more than 85 percent by volume) and smaller quantities of carbon dioxide and methane. Syngas can be used as a fuel to generate electricity or steam, or as a basic chemical building block for a multitude of uses. When mixed with air, syngas can be used in gasoline or diesel engines with few modifications to the engine.[45]

Other Production Processes. Other processes used to produce hydrogen include renewable liquid reforming, nuclear high-temperature electrolysis, high-temperature thermochemical water splitting, and photobiological and photoelectrochemical processes.

Hydrogen Storage

In addition to its production, another technical challenge for hydrogen revolves around its storage. Even though hydrogen has a high energy density by mass, its energy density by volume is low. Therefore, storage of hydrogen fuel requires a sizable container that is also safe and reliable, since hydrogen is highly flammable.

Hydrogen can be stored in tanks as a compressed gas or cryogenic liquid or can be stored on the surface or within other materials, such as metal hydrides and carbon-based materials.

Electricity

Similar to hydrogen, electricity is a secondary energy source since it has to be generated (converted) from other energy sources. Electricity is the presence or movement of electric charge, and it is an extremely useful source of energy since it can be used to perform a variety of types of useful work.

POWER SOURCES (ENERGY CONVERSION)

There are myriad devices (natural and artificial) that can convert energy from one form to another. Since there are many, this section briefly discusses some of the more important (i.e., common) energy conversion devices.

INTERNAL COMBUSTION ENGINE

The internal combustion engine (ICE) is one of the most common and easily recognizable energy conversion systems used today. These engines are commonly divided into two groups: continuous-combustion and intermittent-combustion. Internal combustion engines commonly serve as the primary power source in vehicles including automobiles, trucks, motorcycles, locomotives, boats and aircraft.

This array of vehicles that utilizes the internal combustion engine illustrates the advantages of this engine type. Both the high powerto-weight ratio, and the overall reliability of ICEs, makes these engines ideal for mobile applications.

An internal combustion engine is able to create power and drive the designed engine parts using the energy created through combustion of fuel and oxidizers (typically air). The heat generated during combustion causes a rapid expansion of gases and thus pressure that can perform work on the mechanical components of the engine. This work is used to move pistons, turbine blades or other components within the engine.

Most ICEs are designed to be powered by either diesel or gasoline fuel. The mechanics of both engine designs are similar, but they employ a different ignition mechanism. The ignition process in gasoline engines typically relies on the combination of a lead-acid battery and an induction coil which provides a high-voltage electrical spark to ignite the air-fuel mixture within the engine cylinder. Ignition in a diesel engine is driven by the compression process that occurs in the engine. The heat and pressure created in this stage allows the fuel-air mixture to spontaneously ignite without the aid of a spark. The compression ratio[‡] is one the primary ways to characterize the difference in operating environments of the gasoline and diesel engines. Generally, gasoline engines operate with a compression ratio in the 8-12 range while the diesel engine operates over a higher range from 14-25.

The ability of diesel engines to operate at these higher compression ratios is the primary factor that dictates why diesel engines are typically more efficient than gasoline engines. In fact, diesel engines are less efficient than gasoline engines when operated at the same compression ratio. Modern gasoline engines are approximately 20-25% efficient on average while diesel engines are capable of efficiencies approaching 40%.[§§]

TURBINE-BASED ENGINES

Turbines are critical components in energy conversion systems and are commonly found in automobiles, aircraft, refrigeration systems, and generators. Despite their wide application, turbines are primarily part of a larger machine. For example, a gas turbine may refer to an internal combustion engine with a turbine, ducts, compressor, combustor, heat-exchanger, fan and (in the case of one designed to produce electricity) an alternator. The most common turbinedriven systems are steam, gas, and/or jet turbines.

In general, a turbine-powered engine converts the energy of a moving stream to mechanical work. In the simplest systems, the stream flows across blades attached to the turbine (rotor) and the blades then are forced to rotate which generates energy that can be used to do work. Turbines are also valuable in energy conversion systems because they can operate at high speeds and are able to provide a high power density source.

FUEL CELLS

A fuel cell (FC) is a device that converts chemical energy from a fuel source to electrical energy via electrochemical reactions in the presence of a catalyst. An electric current is generated as electrons are freed in a half-cell reaction at one electrode, conducted through an external circuit from which electric power is drawn, and finally combined at the opposing electrode in the other half-cell reaction. In the meantime, ions are migrating across an electrolyte to participate in the reactions.

Much like batteries, with no moving parts fuel cells can silently and without vibration provide power. Since there is no mechanical wear, the expected life of a fuel cell is long. The primary difference between a fuel cell and a battery is the battery is a closed electrochemical system in which the reactants can be completely consumed and thus the output power eventually can be depleted. FCs have a continuous supply of reactants, and thus can operate without being recharged. While the fuel source can vary, the typical reactants are hydrogen and an oxidant, which is most often oxygen. While a hydrogen source must be provided, in most cases oxygen can be drawn from the air. The cellular aspect of these power devices is derived from their modular nature.

Fuel cells are typically organized according to the type of electrolyte used. The following sections briefly describe the main types of fuel cells.

Alkaline

Alkaline fuel cells (AFCs) contain an aqueous solution of potassium hydroxide (KOH), which serves as the electrolyte. Potassium hydroxide is used because it is the most conductive alkaline hydroxide.[46]

Hydroxide ions react with hydrogen as shown below to free electrons and produce water. This reaction occurs at the anode.

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

Hydroxide ions are produced at the cathode as oxygen is reacted with water and an input of electrons.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

These types of FCs are very susceptible to contamination. A small amount of carbon dioxide in either of the reagent streams (i.e., hydrogen or oxygen) will result in carbonation of the potassium hydroxide. Ultimately, such a contamination would result in the formation of particulates which deposit in the porous electrode. Thus, AFCs require pure hydrogen and oxygen, and therefore are primarily used in space applications.

Molten Carbonate

Molten carbonate fuel cells (MCFCs) utilize a liquid solution of lithium, sodium, and/or potassium carbonates for the electrolytic medium. This is a hot corrosive liquid, and thus are primarily used for stationary applications.

The reaction at the anode involves a carbonate ion and hydrogen as shown below.

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$$

This produces water, carbon dioxide (CO2) and free electrons. The CO_2 must be recycled to the cathode side of the fuel cell where it is combined with oxygen and free electrons to form the carbonate ion as shown below.

$$\tfrac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$$

Due to the high operating temperature of the fuel cell, natural gas can be used as the hydrogen source. Steam is also generated because of this high operating temperature, which can be harnessed for an auxiliary source of power.

Phosphoric Acid

Phosphoric acid fuel cells (PAFCs) utilize concentrated phosphoric acid as the electrolyte because it is a good ionic conductor at high temperatures. Since the electrolyte is a hot corrosive liquid, PAFCs are well-suited only for stationary applications.

The reaction at the anode involves separating the hydrogen into ions to produce free electrons as shown below.

$$H_2 \rightarrow 2H^+ + 2e^-$$

At the cathode, the hydrogen ions are combined with oxygen and free electrons to produce water as shown below.

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

The electrodes are made of carbon paper with a dispersion of platinum catalyst.

Polymer Electrolyte Membrane

Polymer electrolyte membrane (PEM) fuel cells (see Table 7), also known as proton exchange membrane fuel cells, rely on a specialized fluoropolymer membrane material that has sulfonic acid groups. The sulfonic groups facilitate ionic conduction under hydrated conditions. The operating temperature for PEMFCs is relatively cool (70°C).

The reactions on the anode and cathode side of the FC are the same as those shown for PAFCs.

Direct methanol fuel cells (DMFCs) are a subset of PEMFCs. These FCs utilize the same electrolyte material, but use a different fuel source (i.e., methanol) and thus a different catalyst (i.e., platinum/ruthenium alloy rather than carbon-platinum).

Solid Oxide

Solid oxide fuel cells (SOFCs) uses a solid ceramic material, yttria stabilized zirconia, for the electrolyte. These FCs must operate at high temperatures in order to readily conduct ions via the ceramic electrolyte. Due to the high operating temperatures, however,

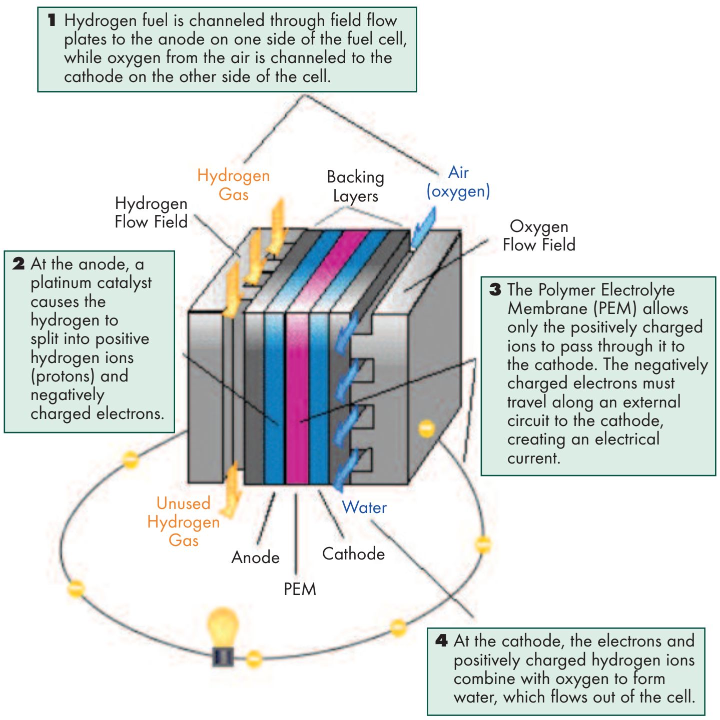

Figure 7. **Diagram of a PEMFC.[47]**

expensive catalysts are not required and hydrocarbon fuels can be used directly.

The Department of Energy Hydrogen Program has established a simple comparison of several fuel cell technologies. This comparison is provided in Table 7.

BI-FUEL ENGINES

Bi-Fuel/Dual Fuel Engines

Energy conversion processes have continued to evolve over time in order to meet the changing requirements of users. One such evolution in recent years has been the increase in development and implementation of engines that are capable of running, at least in part, on alternative fuels. These engines are operated using a mixture of gasoline or diesel and an alternative fuel (commonly compressed natural gas, CNG).[49]

Hybrid cars that use both electric and conventional combustion engines are becoming increasingly common as well. However, these hybrid vehicles are not the only alternative to internal combustion engines. Both bi-fuel and dual fuel engines are also available for automotive applications. One of most common examples of these engine types used in the US today can be found in cars that are designed to run on flex-fuel (typically: E85).[50]

The characteristics of bi-fuel and dual fuel engines are similar so the individual terms are sometimes used in conjunction with one another. There are two common mechanisms used in these engines to convert the fuel to energy for the engine. Engines of this type are characterized as follows:[51]

(1) The engine is designed to operate using a blended fuel mixture. Blends are commonly a mixture of petroleum based fuels (e.g., gasoline or diesel) and an alternative fuel (e.g., ethanol).

(2) The vehicle has two separate fuel systems where one is designed to provide an alternative fuel to the engine and the other is designed to store either gasoline or diesel. These engines can operate on either fuel type, but typically diesel-based engines are more common. A variety of manual and automatic systems for injecting the fuel into these engines can be used. These engines have typically been modified from their original specifications, but they can still operate on their original gasoline/diesel fuels.

The most common alternative fuels used in the first engine are CNG and ethanol. The US has seen an increasing market for flex fuel vehicles because the necessary modifications do not have a significant impact on the cost. The primary concern with engines of this type is the efficiency from burning ethanol. E85 blends can be 30% less efficient than regular gasoline blends. Thus, vehicle owners have to pay close attention to the cost of E85 in order to justify its use economically. These engines can operate on regular gasoline with little decrease in performance compared to an engine that has not been modified to run on blended fuels.

In the second case, natural gas is the primary fuel used, but these engines are also designed to function with diesel as the ignition source (functioning on heat of compression and not with a spark plug). These engines tend to operate on 100% diesel when they idle. Then, as the vehicle begins to approach full-load performance, natural gas is injected to replace the diesel fuel. The natural gas is injected in proportion to the increasing load and can reach 80% or more of the fuel. These design specifications make these engines valuable in circumstances where the use of natural gas is desired for environmental or economic reasons. Also, the natural gas supply does not have to be abundant since the engine can always be operated with the factory designed fuel.

BATTERIES

The namesake of the common electrical battery has an inherently military origin. The term battery, used to describe a unit of artillery working together, was used by Benjamin Franklin to describe a set of Leyden jars, which are devices that store electrical charge and were the precursor to the capacitor.[52]

The fundamental unit of a battery is an electrochemical cell (also known as a galvanic or voltaic cell), which converts chemical energy to electrical energy through chemical reactions that cause electrons to move from one electrode to another. A galvanic cell has two electrodes, an anode (negative terminal) and a cathode (positive terminal) which are connected through an electrically

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Table 7. Comparison of fuel cell technologies.[48]

Fuel Cell Type	Common Electrolyte	Operating Temperature, °C	System Output, kW	Electrical Efficiency, %	Combined Heat and Power (CHP) Efficiency, %	Applications	Advantages
Polymer Electrolyte Membrane	Solid organic polymer poly-perfluorosulfonic acid	50-100	<1-250	53-58 (transportation) 25-35 (stationary)	70-90 (low grade waste heat)	• Backup power • Portable power • Small distributed generation • Transportation • Specialty Vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature Quick start-up
Alkaline	Aqueous solution of potassium hydroxide soaked in a matrix	90-100	10-100	60	>80 (low grade waste heat)	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to higher performance • Can use a variety of catalysts
Phosphoric Acid	Liquid phosphoric acid soaked in a matrix	150-200	50-1000 (250kW module typical)	>40	>85	• Distributed generation	• Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen
Molten Carbonate	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700	50-1000 (250kW module typical)	45-47	>80	• Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP
Solid Oxide	Yttria stabilized zirconia	600-1000	<1-3000	35-43	<90	• Auxiliary power • Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/GT cycle

conductive medium, or electrolyte, and an electrically conductive path. When the electrodes are electrically connected, electrons are generated via an oxidation-reduction reaction and flow across the conductive pathway from the anode to the cathode, while ions migrate through the electrolyte. Batteries can store chemical energy when the conductive path is not connected.

The increasing number of electronic devices being used by deployed forces puts a greater emphasis on developing longer lasting, lightweight batteries. Many efforts are focused on more efficient batteries which have a higher energy density. Energy density refers to the ratio of power a battery can supply relative to its own weight. There are many variations in battery design and deciding on the proper battery for a given application depends on the nature of use and the environment in which the battery will be operated. Discharge temperature, rate of discharge, ventilation, mobility, weight, and repeatable use, are among the main design considerations for batteries. Batteries can essentially be placed in one of two categories: primary and secondary.

Primary Batteries

Primary batteries, also known as disposable batteries, generate power with an irreversible reaction, and thus it is not practical to recharge them. Once the initial reactants have been depleted, the battery is no longer useful for power applications, however many still have some value and can be recycled.

Alkaline Batteries

Alkaline batteries are one common type of disposable battery and have remained popular because they typically offer higher power densities than rechargeable batteries. Their high power capacity is due to their high electrochemical efficiency and makes them favorable for long duration discharge.[53] However, they are not well suited for all applications and provide poor performance under high drain applications over 75 ohms.

Alkaline batteries typically have zinc (Zn) and manganese dioxide (MnO2) electrodes and are named for their electrolyte, which is an alkaline compound (potassium hydroxide). Zinc and manganese dioxide react through the potassium hydroxide electrolyte to form zinc oxide (ZnO) and a manganese oxide (Mn_2O_3).[54]

Zinc-Carbon Batteries

Based on the Leclanche cell, zinc-carbon batteries offer the cheapest primary battery design but weak performance.[55] They are comprised of a zinc anode, which also serves as the battery case; a carbon rod that serves as the cathode and is surrounded by manganese dioxide and carbon black; and a paste of ammonium chloride and zinc chloride, which serves as the electrolyte.[56] They are considered to have a good shelf life.

Mercuric-Oxide Batteries

Mercury (Hg) has been used as an additive in batteries for well more than a hundred years, and it is still used today despite the known environmental effects. The use of metallic mercury as an additive by US manufacturers has diminished dramatically over the past several decades primarily due to federal law, but other mercury-based compounds are still used in regulated fashion. Alkaline button cell batteries are permitted to contain up to 25 mg of Hg. Other types of button cell batteries, such as zinc-air and silver oxide, contain small amounts of mercury (i.e., average content less than 25 mg).[57]

In mercuric-oxide batteries, the cathode is zinc, the electrolyte is potassium hydroxide and the mercuric oxide (HgO) serves as the anode. The Mercury-Containing Battery Management Act of 1996 prohibits the sale of the button cell form of mercuric-oxide batteries, and the larger variety of these batteries are regulated and restricted to military and medical use.[57] These batteries are carefully managed and recycled.

Zinc-Air Batteries

Atmospheric oxygen can be used as the oxidizing agent for electrochemical cells. The use of an abundant and widely available resource for the oxidizing agent or cathode reactant allows zinc-air batteries greater zinc anode capacity and therefore other attractive performance properties. For example, zinc-air batteries have five times the anode capacity compared to conventional zinc-anode batteries.lviii Zinc-air batteries use zinc for the anode, air as the cathode reactant and potassium hydroxide as the electrolyte. Advantages of zinc-air batteries include high energy density, constant discharge, good shelf-life, and low operating cost.

Secondary Batteries

The ability to recharge a battery or reverse the chemical reaction in the cell by supplying electrical energy to the cell is the defining characteristic of secondary batteries. Rechargeable batteries do not have an infinite lifecycle and ultimately will begin to lose their ability to hold a charge for a number of reasons such as dissipation of the active materials, loss of electrolyte and internal corrosion.

Lead Acid Batteries

The lead-acid battery is a rechargeable wet cell battery suitable for applications where weight is not as critical of a factor. Their construction includes a liquid filled container which must remain upright and well ventilated to release volatile hydrogen gas: a product of overcharging. Lead plates serve as the electrodes, and the electrolyte is a sulfuric acid (H_2SO_4) solution.

Although lead-acid batteries possess a poor energy-to-weight ratio they can provide a high power-to-weight ratio and are relatively cheap to manufacture, thus making them the optimal choice for many applications. Even as the oldest form of rechargeable battery, they are still the most popular choice for automobiles and other vehicles that need to provide high current to a device such as an electric starter.

Lithium-Ion Batteries

With a higher energy-to-volume ratio, sealed dry cell batteries are well suited for portable power applications. There are several different material combinations which can be used for the chemical reaction in dry cell batteries. Nickel-cadmium (NiCd) and nickel metal hydride (NiMH) are of the most well known battery types with lithium-ion (Li-ion) currently being the most popular and fastest growing.

Li-ion batteries contain a lithium ion which travels between the anode and cathode when discharging. When electricity is added to the cell the ion moves in the reverse direction, from cathode to anode, thereby charging the battery. The electrodes of a lithium-ion battery are made of lightweight lithium and carbon. Lithium is a highly reactive element that stores a large amount of energy in its atomic bonds. Thus, a high energy density is obtainable with Li-ion batteries. The voltage, capacity, life, and safety of a lithium ion battery can change dramatically depending on the choice of material used for the anode, cathode, and electrolyte. This design flexibility is favorable but can also make them dangerous if they are not implemented correctly. As higher charge densities are achieved in Li-ion batteries safety concerns and related manufacturing costs increase. Li-ion batteries are very popular choice for portable electronics because they have an excellent energy-to-weight ratio, do not maintain memory, and have a slow self-discharge when not in use.

Nickel-Cadmium Batteries

NiCd batteries are capable of producing large surge currents which is ideal for devices which require a large current such as power tools. The use of cadmium, a toxic heavy metal, however, makes them an environmental hazard and requires special disposal. NiCd batteries primarily compete with alkaline batteries. While they cannot match the charge capacity of alkaline batteries they have the advantage of being rechargeable.

Nickel Metal Hydride Batteries

NiMH battery uses a hydrogen-absorbing alloy for the negative electrode instead of cadmium. They can have up to three times the energy density of an similarly sized NiCd battery and have been a popular battery choice for hybrid vehicles. In comparison to the Li-ion battery NiMH batteries have a lower charge density and therefore offer inferior performance in many portable electronic devices. Additionally, their high self discharge rate makes them impractical for many slow discharge devices such as clocks or remotes. They are better suited for high-rate discharge than alkaline batteries due to their lower internal resistance. For instance, in digital cameras, NIMH batteries can sustain a constant voltage at high current discharge for a longer period of time and of course maintain the added benefit of being rechargeable. NiMH batteries tend to have the quickest rate of self discharge and are a poor option for long term energy storage.

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* Aliphatic compounds are organic molecules comprised of hydrogen and carbon atoms bonded together in the form of a straight chain.

† Paraffins, also known as alkanes, are saturated hydrocarbons, in which carbon atoms are singly bonded to other carbon atoms and hydrogen atoms.

‡ Naphthenes, also known as cycloalkanes, are saturated hydrocarbons containing at least one ring of carbon atoms.

§ Aromatics are hydrocarbons that have hexagonal ring structures with alternating single and double bonds between the carbon atoms.

** Olefins, also known as alkenes, are unsaturated hydrocarbons containing at least one double carbon-carbon bond.

†† Flash point is the minimum temperature needed for the vapor above a volatile liquid to form an ignitable mixture with air. At the flash point there is just enough vapor in the air above the liquid to make the mixture flammable and able to release its energy through combustion.

‡‡ A secondary energy source is energy derived from another energy source. Gasoline and other refined fuels can be categorized as a secondary energy source.

§§ Compression Ratio: A value that represents the ratio of the volume of a combustion chamber from its largest capacity to its smallest. It is one of the fundamental specifications given for modern combustion engines.

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Innovations in United States Marine Corps Expeditionary Power Systems

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The United States Marine Corps (USMC) brings unique capabilities to all missions and fulfills a key role as part of any joint operation. To enable these mission capabilities, however, new or upgraded equipment is often required. With each equipment upgrade there is an increase in demand for deployable, quality electric power to support mobile and base operations. Military power systems must be capable of rapid deployment and thus transportable on a host of air, land, sea, and sub-surface platforms. These power systems must also be able to generate and distribute the required quantity and quality of power while being exposed to a wide variety of climates, terrains, temperatures, altitudes, and corrosive environments. Finally, to support the current engagement and to be ready to support the next engagement, these systems must be rugged, maintainable, sustainable, reliable, and efficient.

The Marine Corps Systems Command (MARCORSYSCOM) is the Marine Corps Commandant's principal agent for acquisition and sustainment of systems and equipment used by the Operating Forces to accomplish their warfighting mission. Within MARCORSYSCOM are 27 Program Management Offices, each with a focus on their unique commodity assignment (e.g., weapons, clothing, communications, tanks, etc.). The Program Manager for Expeditionary Power Systems (PM EPS) is responsible for research, development, acquisition, and life cycle management of all power systems for Marine Corps ground forces, which includes tactical power generation, power distribution systems, battery management and sustainment, alternative power systems, container systems, and environmental control systems. The Program Manager works closely with other services for joint solutions, which often can be leveraged to the Corps' advantage. However, when unique missions or capability gaps exist, MARCORSYSCOM has not been adverse to embark upon and capture the opportunity for innovative solutions.

This article provides an overview of some of the innovative efforts that are taking place at MARCORSYSCOM to support the warfighter while providing for the growing need of reliable and robust sources of electric power. The article covers mobile electric power, advanced power sources, renewable energy systems, and onboard vehicle power.

MOBILE ELECTRIC POWER

The requirement for tactical electric power is an enduring need that is and will continue to be a critical enabler for all forces. A family of Mobile Electric Power (MEP) systems and components supports the full range of USMC missions, including air control, communication/information systems, environmental control systems, and life support systems in addition to the general power requirements of operating forces.

The Marine Corps' strength in innovation was recently demonstrated while meeting a unique demand for units deploying during Operation Iraqi Freedom (OIF). These forces needed a trailer-mounted generator and environmental control unit (ECU) that could be towed behind a High Mobility Multi-purpose Wheeled Vehicle (HMMWV) to support the Regimental Commanders' Unit Operations Center (UOC). Traditional tactics and the size and weight of existing equipment would normally place generators and ECUs on tactical transport trucks and trailers buried within the logistics lines of combat service support, but the UOC needed to be at the forefront of the maneuver element in the new, highly maneuverable, digitally networked, combat environment.

An Integrated Trailer-ECU-Generator (ITEG) assembly was developed for the Marine Corps utilizing commercial components that were integrated into a single platform. The ITEG,

Figure 1. **Integrated trailer-environmental control unit-generator.**

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shown in Figure 1, performed as required and has since been adopted by many other operating units, including supporting command posts, medical units, and intelligence organizations.

A drawback to the arrangement of the ITEG is the inefficiency of the component interfaces. For example, the diesel generator converts chemical energy (diesel fuel) into mechanical energy (via the engine), which drives an alternator to generate electric power. Two-thirds of this electric power is used to drive an electric motor in the ECU, which powers a compressor as part of a vapor cycle cooling loop to generate air conditioning in high temperature conditions. During cold ambient temperature conditions, the generator's electric power is sent to electrical resistive heating elements to generate heat.

All components of the ITEG performed as required. However, since ITEGs are a key enabler for highly maneuverable units and are now employed and embedded across all USMC communities, improvements to the system were investigated as part of developing the next generation system. An improved ITEG, (see Figure 2), with a simplified design and increased efficiency has been developed and is in testing. Efficiency was improved by removing the mechanical-to-electrical-to-mechanical conversion process from the old system and by using the engine flywheel to directly drive the vapor cycle compressor. This resulted in a 20% efficiency improvement to the new system. The diesel generator was replaced with a permanent magnet generator to provide a threefold increase in usable electric output power. In addition, the new system can harvest the heat from the engine coolant for conditioned air heating instead of allowing it to escape to the atmosphere as it did in the first generation system. A collective protection over-pressure system was also added to enable continued operation in Nuclear, Biological and Chemical (NBC) environments, which was not possible with the previous system.

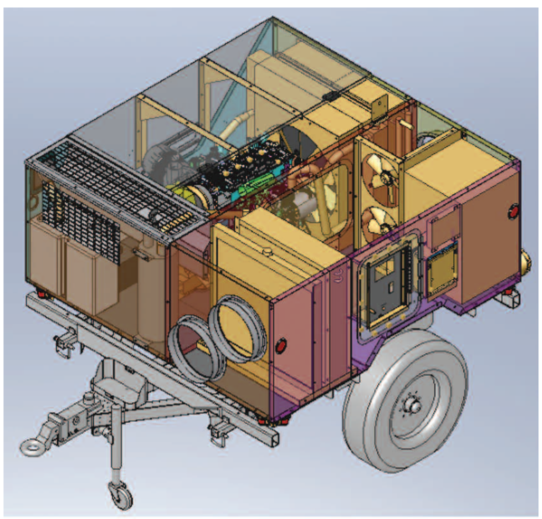

Figure 2. Improved integrated trailer-environmental control unit generator.

The system integrator* is accelerating the development of this product to address not just military needs but also the commercial rental market, which also requires air conditioning and electrical power in remote sites (e.g., work sites, conventions and exhibitions, party rental tents, etc.). The NBC over-pressure functionality will be on military units only.

Mobile Electric Power DIStribution

In addition to power generation, a key component of MEP is power distribution. A near-term ramification of operations in Afghanistan and Iraq, as well as other Marine deployments, was a lack of Mobile Electric Power DIStribution (MEPDIS) sets, including power distribution panels and wiring harnesses. An acquisition decision to move toward commercial-based power distribution systems has resulted in a tailorable family of components that are lighter, cheaper, and faster to produce. Market research highlighted that the power distribution needs of the commercial entertainment and rental industries were highly analogous to those of the USMC. These industries support functions (e.g., concerts, work sites, stage shows, carnivals, etc.) that require equipment which can be rapidly set up and disassembled, and are operable in all weather conditions, durable during rough handling, and highly supportable and maintainable with minimal training; these are the same capabilities the Marine Corps requires.

Another key aspect of the USMC MEPDIS replacement system was the transition from military unique electrical connectors to commercial-based connectors and electrical standards. Originally implemented in the 1980's, military specific connectors were the only components robust enough for harsh environments. During the ensuing period, commercial connectors in accordance with International Electrotechnical Commission (IEC) standards have been developed and proven to fully meet rigorous military requirements. Whereas unique military connectors can sometimes have up to a six-month lead-time for delivery, commercial connectors are available worldwide and routinely stocked for immediate point-of-sale transaction. The Program Manager conducted a user evaluation of different electrical connector types and styles with Marine Corps electricians to achieve buy-in of the acquisition strategy and configuration changeover. Utilizing available commercial and military data, user input, and commercial standards, a commercial item acquisition approach was put in place, which was well received by industry.

Six new USMC power distribution panels, shown in Figure 3, were fielded. These panels are robust, tolerant, and capable of withstanding harsh environments and rough handling. A key feature of the new system was reduced weight, lower life cycle cost, and improved time of delivery. Polyethylene cases made from recycled plastic reduce weight by 33% while providing electrical insulation.

Although commercial-based, all articles have undergone and successfully passed verification testing for military test protocols. The smaller panels have also received third-party certification for electrical safety and handling.

Throughout the program, managing risk and maintaining high safety standards has been paramount. Components have multiple safety systems and interlocks to protect users from electrical hazards. These features have been verified in both technical testing and operational deployments with Marine Corps units. Cost savings of 40-65% per component have been realized with the commercial item strategy. The MEPDIS replacement program has been a hallmark program in innovative contracting, program management, testing, and risk mitigation, and it was recognized in 2007 with the DoD "David Packard Excellence In Acquisition Award."

ADVANCED POWER SOURCES

As a significant user of military batteries to power a large number of weapons, sensors, and communications systems, the USMC was severely impacted in 2003 by the military battery shortage experienced during the early phase of OIF. Analogous to the initiatives intended to improve the "big power" systems of the MEP family, the USMC Advanced Power Sources (APS)

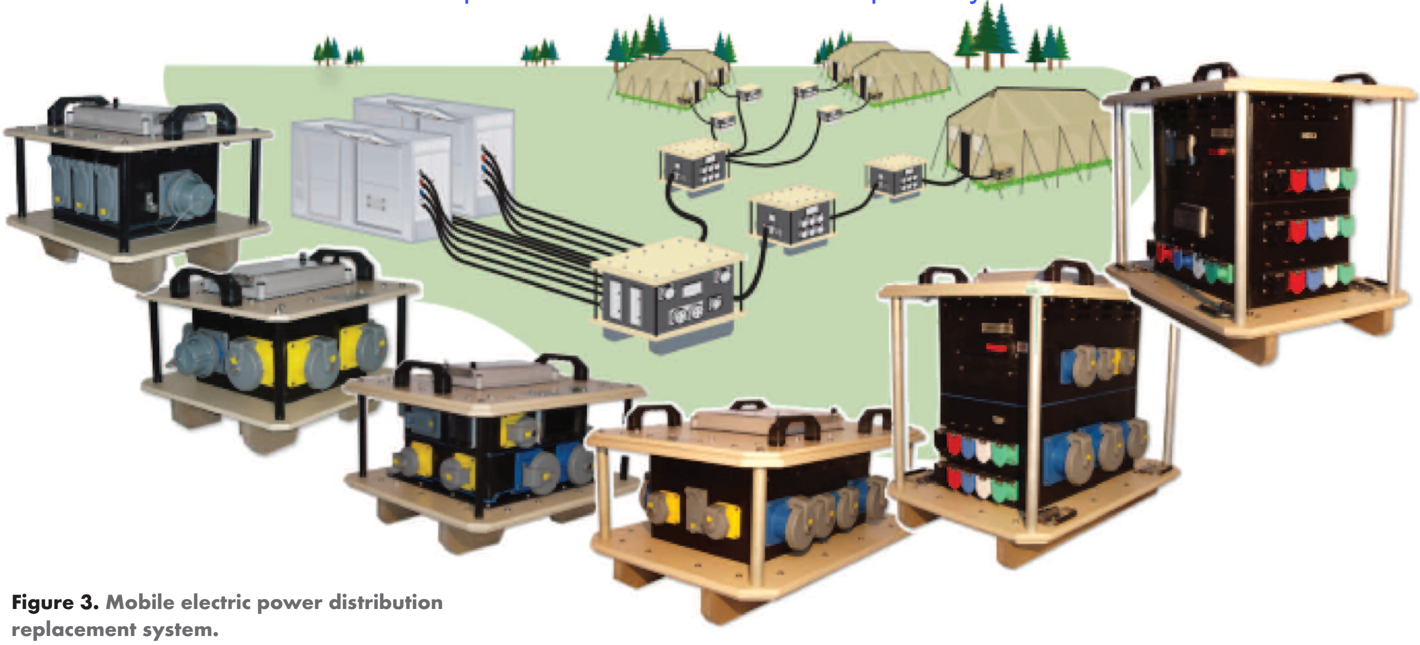

Figure 3. **Mobile electric power distribution replacement system.**

program is focused on the small power realm in part to improve logistic flexibility.

The APS program provides a suite of devices with power in the range of 20 watts to 2 kilowatts (kW) for energizing communications equipment, computers, and other peripheral equipment in mobile, tactical, or remote environments. These devices provide battlefield commanders with options and flexibility, while leveraging commercial solutions to the maximum extent possible for cost and logistic reasons. Key focus areas of the program that have already shown an ability to decrease the Marine Corps' logistical footprint include: battery management systems, adoption of rechargeable batteries, power adaptors for units in garrison operations, renewable energy systems, and onboard vehicle power systems.

During OIF, battery users had no means of determining the remaining amount of charge in their batteries prior to the start of a mission. To remove the risk of a battery dying at a critical point in a mission, warfighters would install a fresh battery every day or every mission. This created a battery shortage and also resulted in piles of discarded batteries that were not entirely expended. Working with the US Army, the USMC has introduced one-time use military batteries with built-in State of Charge Indicators (SOCI) to help manage inventories and usage. In addition, similar to what is occurring in the commercial sector, military use of rechargeable batteries is increasing. With advanced lithium-ion battery technology close to matching the energy densities of disposable batteries, more rechargeable batteries are being used by operating forces.

Although weapons and communications systems are typically designed to be highly mobile, often this same equipment is used at bases and stationary locations where host power is available. In these situations, radio power adaptors enable the use of 120/240 volts alternating current (VAC) which provides a means to conserve critical battery stockpiles. While other services allow the purchase of adaptors or support equipment with unit funds, in favor of commonality the USMC decided to centrally manage, fund, and field standard equipment. Numerous suppliers make and sell items to support military equipment, but not all items are created equal. The USMC has established an evaluation and vetting process for electronics equipment and routinely fields several new classes of equipment each year as new radios or communications devices hit the fleet. As part of a formal solicitation process to industry, the USMC provides a set of technical and verification requirements for the needed capability. The USMC will then request bailment (no-cost) copies of the article from all suppliers, which are then taken to an independent test laboratory for verification (USMC pays for testing). In exchange for loaning the article, the supplier is provided a complimentary copy of the test results for their equipment item. From testing the USMC obtains validated data to support the formal source selection process for procuring and fielding the equipment. This process has worked with great success for several reasons. The government is able to collect sufficient quality information on which a well-informed selection decision can be made. The process is transparent to industry, and the participating suppliers receive independent test data of their product in exchange for temporary loan of the equipment.

RENEWABLE ENERGY SYSTEMS

In 2006, the Commanding General for Multi-National Forces in Iraq submitted a Joint Urgent Resource Request (JURR) for renewable energy systems. The basis of the need was principally to seek relief for the numerous fuel convoys that were prime insurgent targets, but there was also a need at the operator level for more responsive power solutions for a wide range of mission equipment in austere and remote sites. Lighting, surveillance equipment, and sensor arrays need continual power, but the power requirements do not typically constitute a need for a generator. This equipment, however, is too large for most battery systems and is typically too remotely located to draw from grid power sources. The JURR requested a family of small, medium, and large power systems. In response, the USMC, with support from the Office of Naval Research (ONR), embarked upon a development and demonstration program of a HMMWV towable trailer mounted system (less than 3000 pounds total system weight) that can produce between three to five kW of electric power (analogous to the power need at a small forward operation post). Utilizing commercial components for energy

Figure 4. Man-portable renewable energy system.

collection (wind and solar), energy storage (lead acid and lithium-ion batteries), and electronic control, three different systems were initially designed, and then two systems were fabricated and tested. Testing is still ongoing, but preliminary lessons learned to date include:

- Wind power generation equipment is too heavy and not effective for small, highly mobile units
- Solar panel selection is critical, with efficiency versus weight versus robustness being key drivers
- The footprint of solar panels is extensive
- For a 24-hour duty cycle where multiple kilowatts of power is needed, the system will require either a large quantity of lithium-ion batteries or a diesel generator for nighttime operation
- Use of lithium-ion batteries is a significant system cost driver (approximately 30-40% of system cost)
- Production systems in this power range cost 20-30 times that of a diesel generator

On a smaller scale, such as a man-portable renewable energy system, (see Figure 4), the USMC is now conducting user evaluations on two systems that weigh less than ten pounds and can be easily folded up for transport.

Targeted for a specific function (charging a battery for a radio system or directly powering a radio power adaptor) and for specific equipment, these smaller systems have the flexibility to support niche missions. These systems are being evaluated to determine if they can be set up and operated together to support larger power loads. Similar to the commercial sector, renewable energy systems are still in their infancy in the military, and they require more evaluation and understanding to determine where and how they can be used to their maximum potential.

ONBOARD VEHICLE POWER

Currently, man-portable and trailer-mounted generators fill the bulk of power generation requirements for tactical electric power. However, towing a trailer limits the vehicle's payload capacity, restricts mobility, and consumes critical embarkation space when Marine Expeditionary Units deploy via an aircraft transport or aboard naval amphibious shipping. Moreover, with the continued addition of more electronic warfare systems, communications systems, situational awareness devices, and electrically powered accessories on tactical vehicles, the vehicles are running out of electric power. Shown in Figure 5 is the historical trend of installed electric power on the two most prolific vehicles in the USMC combat inventory: the HMMWV and the Mine Resistant Ambush Protected (MRAP) vehicle.

Two initiatives intended to get ahead of the "power curve" and to address future onboard vehicle power systems in tactical vehicles are under development by ONR and transitioning to MARCORSYSCOM in 2009. The first vehicle development and demonstration has been on the HMMWV (see Figure 6) for a capability of 20-30 kW of onboard and exportable power. This level of electric power follows historical trends for power demands in Command and Control intensive applications, while also enabling enhanced capabilities unseen with any vehicle today. In addition to directly powering onboard systems, the vehicle can serve as a temporary power generation system for an Operations Center, a back-up generator for any application, an uninterruptible power supply for mission critical equipment, and as a direct power source for power hungry, vehicle mounted mission equipment that normally would have a towed generator as its power source. As of the time this article was being printed, the prototype vehicle was to be delivered to the US Army Aberdeen Test Center (ATC) for test and evaluation. It is the intention that this capability will begin initial production and fielding in 2010 as a mission role variant of the HMMWV for the USMC.

Also coming out of the science and technology arm of ONR is an even greater level of capability on a larger platform. On the USMC Medium Tactical Vehicle Replacement (MTVR), shown in Figure 7, will be a retrofit kit that replaces the current mechanical transmission with a diesel-electric transmission.

Similar to locomotive power systems, the under-hood diesel engine of the MVTR directly powers a large alternator. All mechanical power from the engine is converted to electrical power, which is then used to drive electric motors that power the unaltered driveline of the MTVR. But the unique attribute of this system is the ability to tap the electric power distribution system

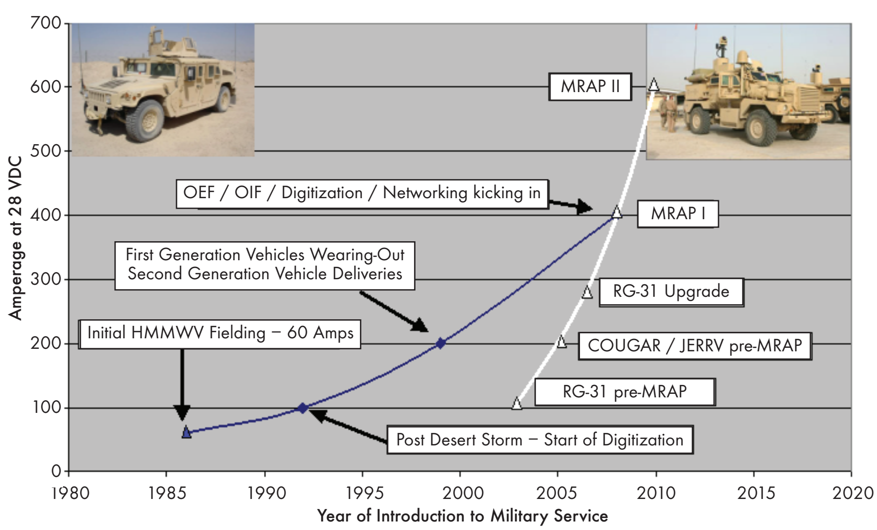

Figure 5. Installed vehicle electric power capability.

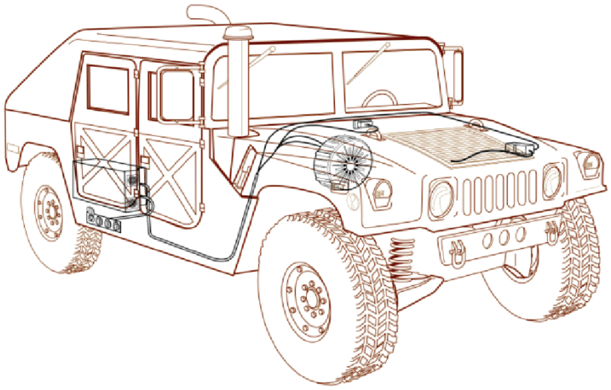

Figure 6. **HMMWV onboard vehicle power system.**

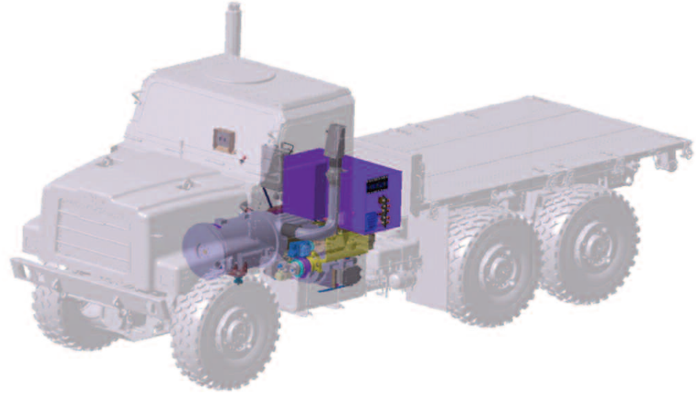

Figure 7. **MTVR onboard vehicle power system.**

to power both onboard and off-board systems. In this vehicle application, the first prototype system has demonstrated in testing at ATC up to 120 kW of exportable electric power while the truck is stationary and up to 21 kW of onboard electric power while the truck is on the move. Similar to the HMMWV, this system will be ready for production and fielding in 2010 as a mission role variant.

SUMMARY

In its role to support the operating forces of the USMC, the Program Manager for Expeditionary Power Systems continues to develop, field, and support a wide range of power solutions. Realizing that no one solution fits all needs, the Program Management Office attempts to offer power solutions with a menu of choices. In addition, as new tactics and missions evolve so, too, must solutions and opportunities. Innovative alternatives continue to be a hallmark of the United States Marine Corps and MARCORSYSCOM.

Additional information and reference material for the whole family of USMC power systems is available at http://www.marcorsyscom.usmc.mil/sites/pmeps.

NOTE

* Magnum Products LLC of Berlin, Wisconsin

Mr. Michael A. Gallagher is the Program Manager for Expeditionary Power Systems at the Marine Corps Systems Command, Quantico, Virginia. Within Expeditionary Power Systems, the organization is responsible for research, development, acquisition, and life cycle management of numerous power systems for the Marine Corps, including tactical power generation, power distribution systems, battery management and sustainment, alternative power systems, environmental control systems, and container systems. Mr. Gallagher's background and 30 years of acquisition experience have focused on numerous Marine Corps Ground Combat Systems, Combat Support Systems, and Naval Amphibious Systems.

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Photovoltaics for the Defense Community through Manufacturing Advances

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Photovoltaic solar power will bring a new level of self-sufficiency to the defense community, both for individual soldiers and military bases. Flexible photovoltaics integrated into tents and used as portable chargers can provide access to power in remote battlefield conditions.[1] To minimize reliance on supply chains, combining rechargeable batteries with portable photovoltaics could decrease the battery load weight of a soldier by half.[2] In addition, military bases that install photovoltaics will be able to implement micro-grid systems. Micro-grids combine self-sufficient energy generation with base-only electrical interconnection, making a base independent of the outside electrical grid and thus enabling a high degree of security and mission readiness.[3]

PHOTOVOLTAIC GRID PARITY

With these wide-ranging benefits, the relevancy of making photovoltaics more accessible for the defense community is clear. One of the ways to make photovoltaics more accessible is to decrease the cost of photovoltaic electricity to the point of grid parity, where solar electricity fed into the grid is the same cost as conventional sources (e.g., coal, nuclear, natural gas, etc.). In fact, achieving photovoltaic grid parity by 2015 has been stated as a goal for the US Government through the Department of Energy (DOE) Solar Energy Technologies Program*. The DOE estimates that in the US, achieving unsubsidized photovoltaic grid parity will require system costs to come down 50-70% from the levelized cost of energy (LCOE) benchmarked in 2005 (see Figure 1).

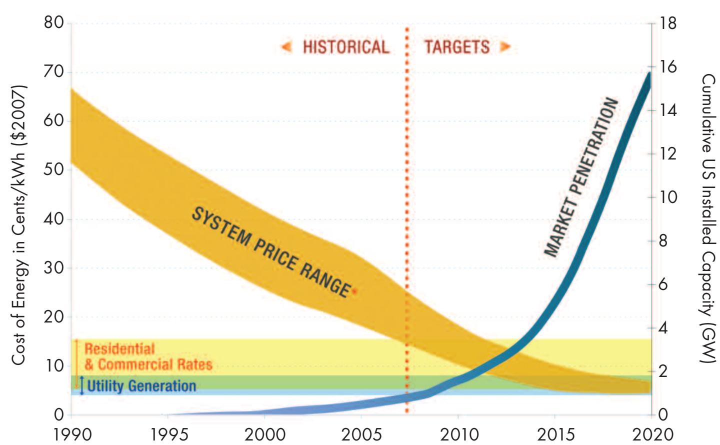
The way to determine the point of grid parity is to calculate the LCOE of a photovoltaic system and compare it to the local electric rates. The LCOE (¢/kilowatt-hour) is the sum of the costs of the system divided by the amount of energy it produces during its lifetime. It can be calculated with the formula below:†

$$LCOE = \text{net present value}\frac{(price)}{(energy)} = \text{Initial investment}[\$/Watt] + \frac{\sum_{n=0}^{N}\frac{\text{Maintenance costs }[\$/\text{kilowatt-hour}]}{(1+\text{discount rate }[\%/\text{year}])^{n}}}{\sum_{n=0}^{N}\frac{\text{Annual electricity generated }[\text{kilowatt-hour}/\text{year}]}{(1+\text{discount rate }[\%/\text{year}])^{n}}}$$

The initial investment is often broken down to isolate the module, the inverter, and the balance of system (BOS) costs. The module is the "solar panel" component that generates electricity, the inverter converts direct current (DC) produced by the module to grid-ready alternating current (AC), and the BOS represents all the other initial costs, which include wiring between modules, racks to mount modules, and installation labor.

A module's value balances two factors: the cost of manufacturing the active semiconductor materials, wire connections, packaging, etc., and the power that the module can generate from sunlight. As discussed in the subsequent section, different module technologies and their associated manufacturing techniques offer different but viable module solutions. For instance, some module manufacturing costs may be promising because they are very low, but they may produce a module with lower performance. Alternatively, some module configurations use some very high cost components, but those components convert sunlight to power with high efficiency. Modules do not represent the only way to decrease the initial investment required for photovoltaic installations, but they are currently around 50% of the initial outlay and for the near future will continue to be a target for reducing LCOE.

To get an idea of the effect of a 50-70% decrease in LCOE, it is useful to compare the present situation to a reasonable forecast. In Figure 2, a map shows the difference in LCOE for residential photovoltaic systems bought at \$8.50/W and electric rates across the US. In areas where high grid electricity prices, excellent sunlight, and/or state and local incentives are present in some combination (red and orange), photovoltaics are already financially competitive.‡



Market Sector	Current US Market Price Range Cost (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

Figure 1. **Historic and predicted photovoltaic cost of energy and total installations over time.**

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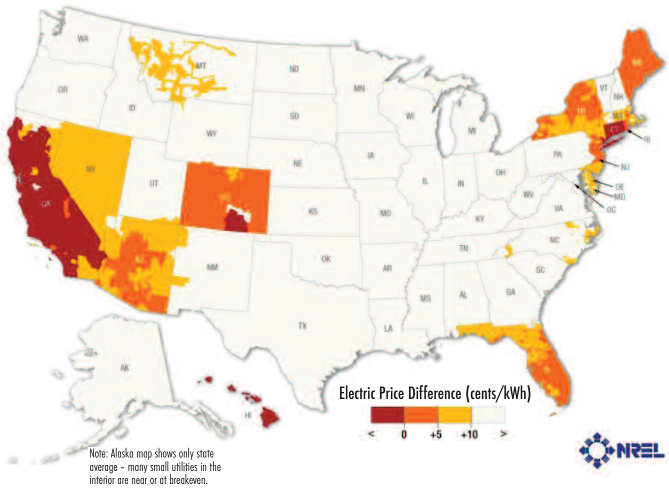

Figure 2. **Difference in electricity prices in 2007 between solar levelized cost of energy and grid electricity.**

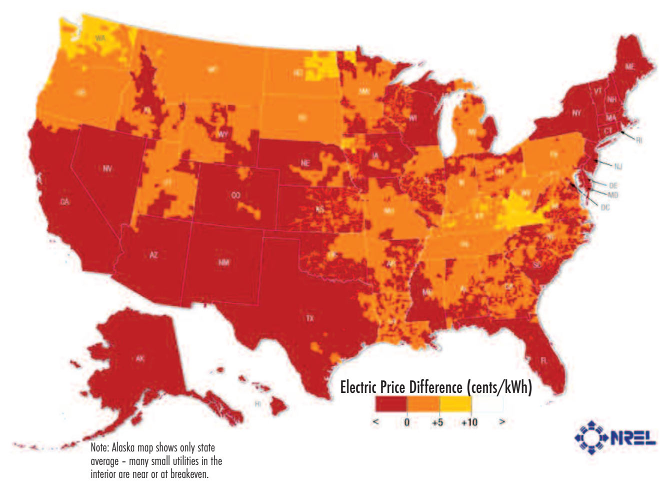

Figure 3. **Projected difference in electricity prices in 2015 between solar levelized cost of energy and grid electricity.**

In Figure 3, a further comparison for residential photovoltaic systems bought at $3.30/W shows a realistic forecast for 2015, assuming no state or local incentives for residential photovoltaic installations and real electricity rate increases of 2.5% per year.[§] In this scenario, the price difference between grid electricity and photovoltaic electricity would be less than 5¢/kWh for 91% of sales in nearly 950 of the largest utilities, indicating that grid parity would be achievable for most of the nation by 2015.

MANUFACTURING AND PHOTOVOLTAIC COST

In the private sector, the prospect of selling a product with desirable attributes at a price that puts it in the reach of a market of hundreds of billion dollars or more has fueled an enormous investment of funds in photovoltaic companies through public stock offerings, venture capital (VC), and private equity (PE) (see

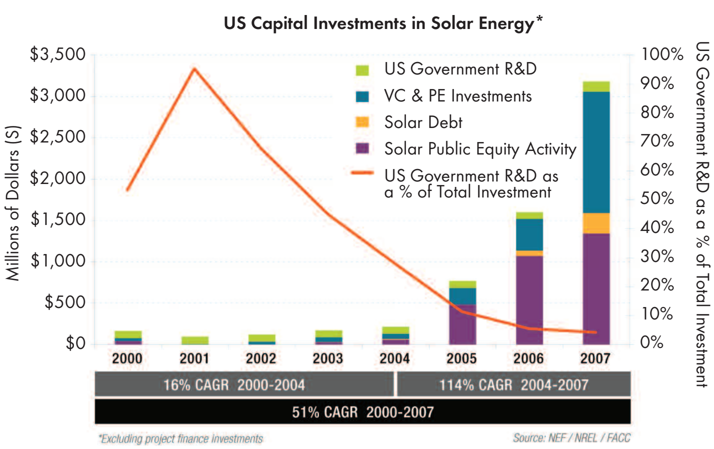

Figure 4. **Surge in solar energy investment.**

Figure 4). There are two reasons DOE and the private sector believe grid parity within six years is an achievable target. First, the considerable diversity in photovoltaic technologies and within the manufacturing options for each particular technology has produced a number of viable options for decreasing module costs. Second, further scale-up of manufacturing capacity will achieve significant cost reductions based on economies-of-scale and industry-wide lessons learned, much like the semiconductor industry has enjoyed. Many of these photovoltaic companies claim the potential to meet unsubsidized grid parity in the largest markets in the 2012-2015 timeframe.

Photovoltaic Manufacturing Diversity

There are three major groups of photovoltaic module technologies currently in the marketplace:

- Crystalline Silicon
- Thin Films
- Concentrating Photovoltaics (CPV)

In Figure 5, module technologies are binned into these three groups, and then at the next two levels divisions show how the secondary categories can be further differentiated through materials choices, manufacturing techniques, and engineering designs. The three major types of photovoltaics currently available are highlighted in Table 1. Conceptually, this highlights the rich design space of photovoltaic systems and suggests multiple pathways may achieve grid parity.

Crystalline silicon photovoltaics are the most mainstream style of photovoltaic module. This technology represents 80-85% of the newly added capacity in 2008. The most common way to manufacture a crystalline silicon module is to pull or cast a silicon

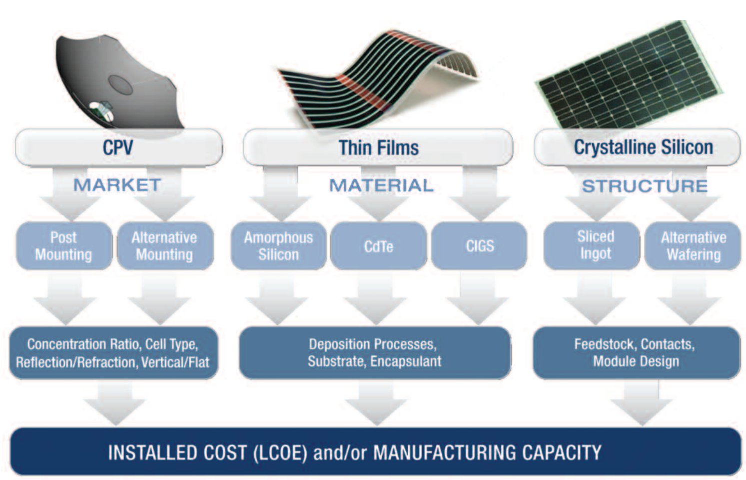

Figure 5. **Photovoltaic technologies differentiated by material, manufacturing technique, and engineering designs.**

Table 1. **Key areas of differentiation in photovoltaic technology.**

Crystalline Silicon

Key areas	Examples
Ingot Crystal Structures	• Multicrystalline • Monocrystalline
Wafering Techniques	• Wire sawing • Pulling slices off the ingot through strategic ion implantation
Cell Contacts	• Screen-printing conventional contacts • "Emitter wrap-through" contacts that come up through the cell • Inkjet printing conventional contacts
Feedstock Choice	• "Solar grade" feedstock • Integrated circuit stock material

Thin Films

Key areas	Examples
Active Material	• Copper indium gallium diselenide (CIGS) • Cadmium telluride (CdTe) • Amorphous silicon (a-Si)
Method of Deposition	• Physical and chemical vapor deposition • Atmospheric deposition, such as ink printing or electroplating
Substrate	• Glass sheets • Stainless steel web • Polyimide

Concentrating Photovoltaics

Key areas	Examples
Concentration Ratio	• Two suns • 1000 suns
Cell Type	• Wafer reuse to decrease utilization of expensive germanium • Low concentration using crystalline silicon or thin film cells
Lens Type	• Fresnel • Dome-shaped
Module Mounting	• Very large module assemblies stuck on posts • Low to the ground "carousel" assemblies
Number of Axes a Tracker Uses	• One axis tracking • Two axis tracking
Module Design	• Postage-stamp sized cells • Miniature assemblies of microconcentrators

ingot from a melt of high purity silicon, slice it into wafers, process the wafers into active photovoltaic cells, encapsulate the cells within a top cover glass, transparent adhesive, and a flat, rectangular backsheet, frame it with aluminum, and attach a junction box which connects the cell contacts with the outside electrical leads. Key areas of differentiation are the use of distinct ingot crystal structures, alternate wafering techniques to slicing, cell contacts, and feedstock choice.

Thin film photovoltaics represent the rest of today's photovoltaic market. The three technologies currently commercialized use amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). The general idea behind thin film photovoltaics is that depositing thin layers of light-absorbing photovoltaic active materials on low-cost supporting substrates will be a cheap, quick, scalable way to mass-produce photovoltaic modules. Product variations are largely determined by choice of active material, method of deposition, and substrate.[4]

Though CPVs do not currently claim significant market share, they are a technology with strong potential to enter the growing market for photovoltaic solutions.[5] The concept of CPV is to use lenses and mirrors to direct multiple suns-worth of light onto a photovoltaic cell, thereby boosting its electrical output. The typical photovoltaic cell is a multijunction cell usually made of semiconductor materials from the Periodic Table groups III and V**. The cells are relatively small (1 cm^2) and more costly, yet very efficient. The multiple junctions allow the cell to convert more of the sun's light spectrum to electricity. The extra expense of III-V cells requires concentration and sun-tracking to make this technology cost-effective. Multijunction cells are manufactured by depositing III-V materials through metal organic vapor phase epitaxy on germanium wafers. Processing variables in the CPV space include concentration ratio, cell type, lens type, module mounting, number of axes a tracker uses, and module design.

Photovoltaic Manufacturing Scale-up

Price decreases will also come after the photovoltaic industry has reaped the benefits that large scale manufacturing provides. Figure 6 shows the module price for crystalline silicon plotted versus cumulative production for the crystalline silicon photovoltaic industry. This type of graph, called an "industry learning curve," represents the collective progress of the manufacturing industry, including its supply chain.

As individual companies make improvements and suppliers become more efficient, many of these advances will diffuse or "spill" across the industry and lower the costs of production for all. As the graph shows, silicon photovoltaics have been steadily decreasing in price since the 1980's. The cost to the company to make the photovoltaic module is consistent with the price the company charges when a 30% profit is assumed. Therefore, the trend in prices is generally assumed to reflect the trend in costs. Using wire saws, for instance, allowed silicon wafer manufacturers to slice hundreds of

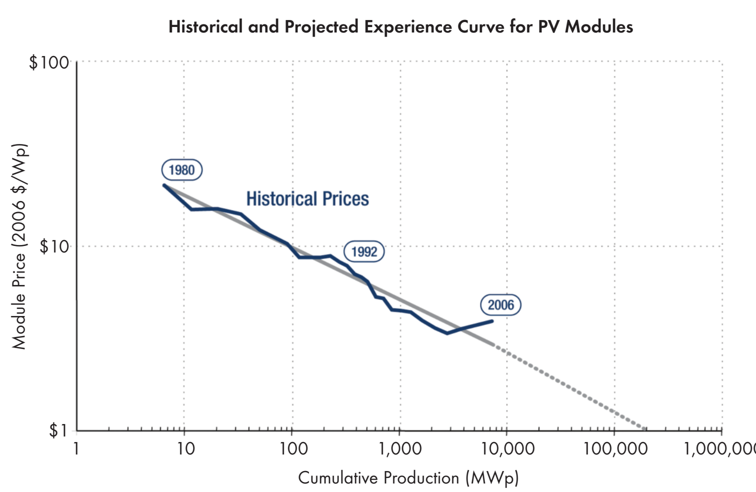

Figure 6. **The average module selling price for crystalline silicon photovoltaic modules as a function of the industry's cumulative production.**

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thinner wafers simultaneously, increasing material utilization which dramatically increased throughput. This advance was widely copied throughout the industry, allowing all wafer manufacturers to progress down the learning curve and therefore decrease the cost of modules.

Regardless of whether the technology group is crystalline silicon, thin films, or CPV, the manufacturer's suppliers are positioned in particular to introduce high impact innovations and advances across the industry. The maturing of the industry will also bring increased standardization. The model to emulate is the semiconductor industry, which has a highly organized set of manufacturing standards that allows suppliers to more efficiently serve their manufacturing customers.[6] All of these advances will enable beneficial scale-up of manufacturing and widespread cost decreases in photovoltaics.

SUMMARY

As the cost of photovoltaics continues to decrease, it will become a boon to defense communities as the levelized cost of energy from a photovoltaic system hits the point of grid parity. The metric levelized cost of energy provides a useful way to compare electricity from a photovoltaic system and electric rates so that we will recognize when the US has hit the point of grid parity. Through the rich diversity of module photovoltaic technology and the lessons that the industry will learn as it scales up production, the era of cheap photovoltaics will soon be arriving. Until then, there is still a strong rationale for using photovoltaics in the military because of increased self-sufficiency.

NOTES & REFERENCES

* For more information on the DOE's Solar Energy Technologies Program, please visit: http//www1.eere.energy.gov/solar/.

† *N* is the lifetime of the system in years, the discount rate is a financial term that corrects for the change in the value of money over time and includes the opportunity cost of buying a photovoltaic system instead of investing money elsewhere, and the other variables are described in the equation.

‡ Assumptions: For the price of electricity, the average electricity price for the 1000 largest utilities in the US based on Energy Information Agency data for 2006 (except CA, where existing tiered rates structures were used). The installed system price is set at $8.5/Wp in the current case and is assumed to be financed with a home equity loan (i.e., interest is tax-deductible), with a 10% down payment, 6% interest rate, the owner in the 28% tax bracket, and a 30-year loan/30-year evaluation period. The solar performance (electricity generated) is based on the National Solar Radiation Database (NSRDB) weather station closest to the center of the utility service territory, assuming a south-facing array, at a 25 degree tilt. An 82% derate factor is used to account for inverter and other photovoltaic system losses, but no performance degradation over life of the system is assumed. Incentives included are the federal Investment Tax Credit (ITC) worth $500/kW due to $2000 cap and individual state incentives as of December 2007. The federal ITC has been revised to no longer have the $2000 cap; therefore these forecasts may be more conservative than initially calculated.

§ Assumptions: Same as previous map, excepting the use of installed system price of $3.30/Wp, real electricity rate increases of 2.5% per year (22% total since 2006), and no inclusion of incentives. Also note the current federal solar subsidy provides a tax credit for 30% of the installed system price and is scheduled to expire in 2017.

** Groups III and V are the elements that occupy columns IIIA, IIIB, and V of the Periodic Table. The most common semiconductors among these elements include scandium (Sc), yttrium (Y), vanadium (V), niobium (Nb), and tantalum (Ta).

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[6] *Renewable Energy World*, Vol. 10, No. 3, May/June, 2007.

Dr. Marie Mapes is a photovoltaic technology manager in the US Department of Energy Solar Energy Technologies Program. Her current responsibilities include coordinating photovoltaic R&D at the National Renewable Energy Laboratory and Sandia National Laboratory, managing university research in advanced photovoltaic concepts, and arranging partnerships between industry, universities, and national labs wherever possible to maximize DOE's research investments. She entered DOE in 2006 as a Presidential Management Fellow. During her two year Fellowship, she initiated new program activity to capitalize on innovative financing mechanisms for solar technology in the federal sector (such as power purchase agreements), launched the Next Generation PV Device and Processes awards for universities and start-up companies, and explored private sector investment strategies during a four month detail at NGEN, a cleantech venture capital firm. Before coming to DOE, Dr. Mapes earned a PhD in Physical Chemistry from the University of Wisconsin-Madison, where her research focused on stability of amorphous systems with applications in the shelf-life of pharmaceuticals. Her undergraduate institution was Grinnell College, where she earned a BA in chemistry.

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A Novel Desulfurizer-Catalyst Combination for Logistic Fuel Reforming

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Editor's Note: Many different approaches will be required to provide the warfighter with a full spectrum of power and energy solutions. One of the more promising of these is fuel cell technology. However, some of the major hurdles for fuel cells to clear include developing suitable hydrogen-rich fuels to sustain them and being able to produce these fuels in both an efficient and environmentally-friendly manner. This article is a summary of leading edge research in the development of new catalytic materials to enhance the production of the needed fuels. This state-of-the-art work was performed by Dr. Abdul-Majeed Azad and his graduate student Desikan Sundararajan of the University of Toledo. If you are interested in learning more about this technology or would like to contact the authors, please contact the AMMTIAC Editor.

INTRODUCTION

The emerging generation of high efficiency fuel cells will require clean power sources that are readily and reliably available. The best sources at present to meet that need are the vast reserves of logistic fuels (jet fuels, diesel, and coal) available to the Department of Defense (DoD). However, each of these fuel sources must be converted into hydrogen-rich streams through a chemical reformation process. Unfortunately, each of these fuel sources contains unacceptable levels of sulfur mostly as organosulfur. Upon combustion, the sulfur is typically combined with elements in the reaction to form one of several molecules, such as hydrogen sulfide (H_2S), sulfur dioxide (SO_2) or sulfur trioxide (SO_3). These are atmospheric pollutants which can be deleterious to air quality and some of which may also lead to acid rain in certain regions of the country.

Thus, it is necessary to remove any sulfur species from these logistic fuels during the reforming process. Chemical reformers in fuel production are typically catalytic vessels. For instance, these reactors contain a bed of a noble metal, usually platinum, that serves as a catalyst* to drive the conversion reaction of the fuel. Unfortunately, a conventional reformer would be hindered by the presence of sulfur in these fuels, as sulfur poisons or renders the catalyst inactive.

The best way to overcome these challenges would be to develop a new generation of effective desulfurizer and sulfur-tolerant reforming catalysts. Meeting these two objectives, specifically an agile desulfurizer capable of sorbing sulfur in the fuel and a sulfur-tolerant catalyst that can tolerate the brunt of a small level of sulfur left uncaptured by the sulfur sorbent, calls for innovative approaches. The research summarized in this article highlights the feasibility of generating clean electric power using desulfurized hydrogen-rich reformates from logistic fuels with reduced environmental impact.

APPLICATION

The immediate applications for hydrogen-powered fuel cells are many: military field operations, including mobile forward base units, auxiliary field hospitals, field command posts, operational forays, unmanned aerial vehicle flights, and aircraft auxiliary power units (APUs) would all benefit from the extended capabilities this type of technology would provide. By extension, this process could be applied beyond refined petroleum fuels to gasified coal-based fuel cell systems. This latter concept could extend the adaptation of fuel cell-based power systems to reach an even broader user segment: the public sector.

The DoD is the largest single user of petroleum products in the world, comprising nearly two percent of total US fuel consumption. The cost of crude oil, amounting to $12.6 billion in 2007, represents a substantial transfer of tax revenue to foreign countries, several of which are adversarial to the United States' strategic interests. Both of these factors, specifically the volume of fuel consumption as well as the sources for some of these fuels, would dictate more efficient use of fuel resources and the synthesis of alternative fuels.

In the light of eventual energy shortages, the ever-increasing global demand for fuel, and the quest for cleaner and greener energy, there is great interest in using logistic fuels. The use of hydrogen-rich reformates of logistic fuels, such as JP-5, JP-8, or Jet-A, are attractive as feeds for polymer electrolyte membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) for NASA and the Army. NASA envisions employing fuel cells running on clean reformate from jet fuels in their future unmanned aerial vehicles (UAVs) and low emission alternate power (LEAP) missions, as well as transcontinental flights[1, 2, 3]. However, depending on the source and kind, jet and other logistic fuels are invariably sulfur-laden; the sulfur content in them varies between 0.3 to more than 1 weight percent (wt%), hence the need to develop robust sulfur-tolerant catalysts to facilitate the continuous uninterrupted operation of logistic fuel processors.

APPROACH

One major alternate source of transportation fuel is gasification of virtually any gaseous, liquid, or solid hydrocarbon into a liquid fuel. Yet most fuel synthesis processes are based on the gasification of fossil fuels, which produce a variety of undesirable "greenhouse" gases. So even in the development of alternative fuels,

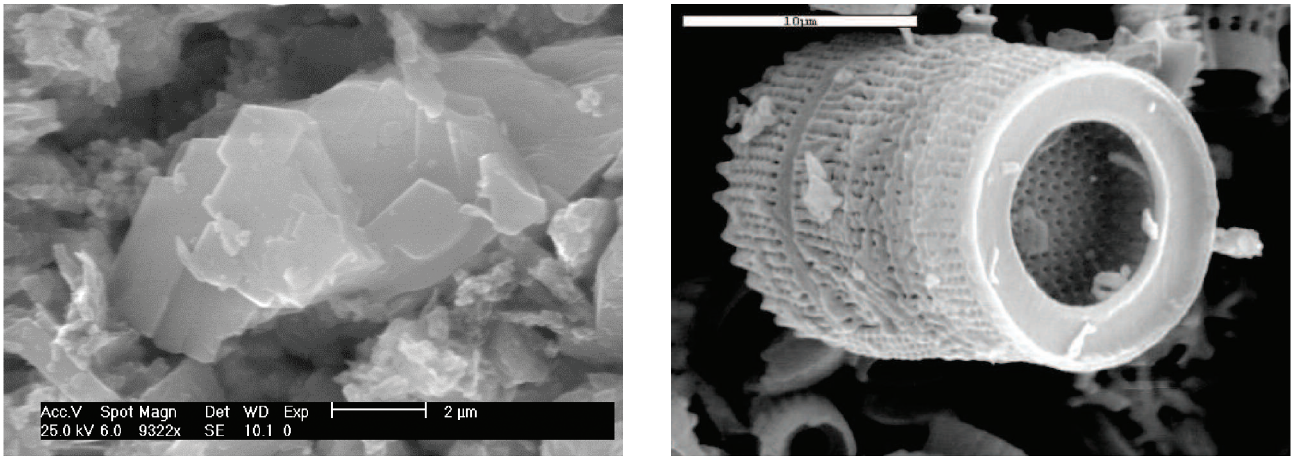

Figure 1. SEM images of clinoptilolite (left) and diatomite (right) support matrix.

there is the looming emphasis on reducing the production of greenhouse gases. The efforts to reduce carbon dioxide emissions in the way energy is produced and used may represent one of the more important technological developments of the 21st century.

The general approach in this effort was to fabricate and evaluate a series of desulfurizers based on a lightweight nanoporous matrix, embedded with agile sulfur-binding species to facilitate sulfur absorption. Designing an intelligent composite between the sorbent material and the sulfur-tolerant nanocatalyst creates a realistic combination of properties to achieve these goals, which an energy supplier/end-user would find appealing.

This research examined the performance of nanoscale, ceria-supported, sulfur-tolerant catalysts with nominal loading of noble metals (NM, total NM ≤1 wt%; NM = mono-, bi- or tri-metal dispersion). These formulations were assessed in terms of their sulfur-tolerance, phase integrity and the quality of reformate using kerosene (JP-8 surrogate), at temperatures typically employed in reforming. Some salient features of novel, low-cost, lightweight desulfurizers were assessed in terms of their sulfur capture under conditions of high sulfur exposure at temperatures typically employed in reforming. Since the final chemical state of sulfur species in the fuel reformate is H_2S[4], desulfurization studies were carried out using streams containing 1000 and 3000 parts per million (ppm) H_2S in the range at 600-800°C for soak-time up to 350h.

Desulfurizers

The first step was to find a suitable support material to host the sorbent. Diatomaceous earth and clinoptilolite (zeolitic clay) were used as inert support materials for synthesizing the sulfur sorbents. Scanning electron microscope (SEM) micrographs of these materials are shown in Figure 1. The sorbents were made by dispersing selected metal oxides onto the support materials.

The adsorption performance of each combination of the desulfurizing material was evaluated by exposing the sorbent in powder form to a H_2S-laden stream of nitrogen for several hours at several test temperatures. The absorbency of each material was evaluated by measuring the H_2S concentration in the exit stream using a gas chromatograph.

It was found that the sulfur capture propensity of these formu-

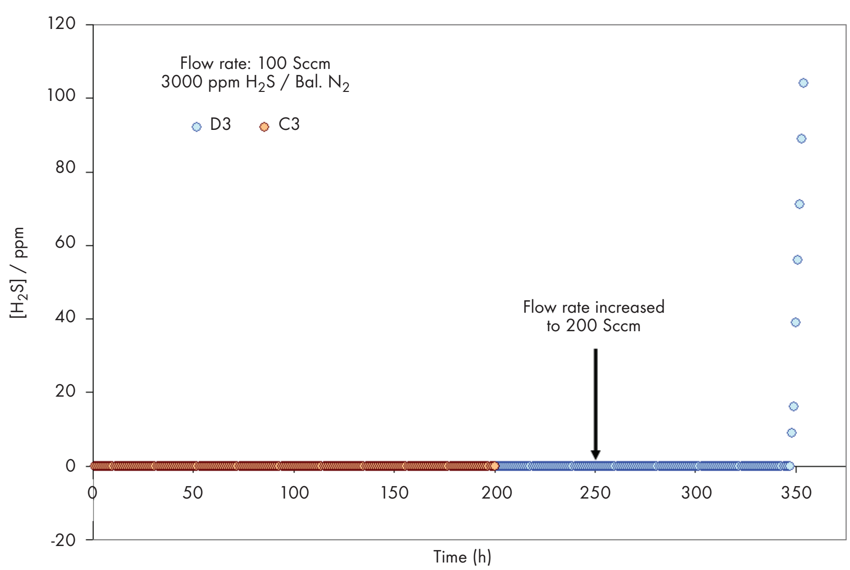

Figure 2. Sulfur capture by the sorbents in long-term tests at 800°C.

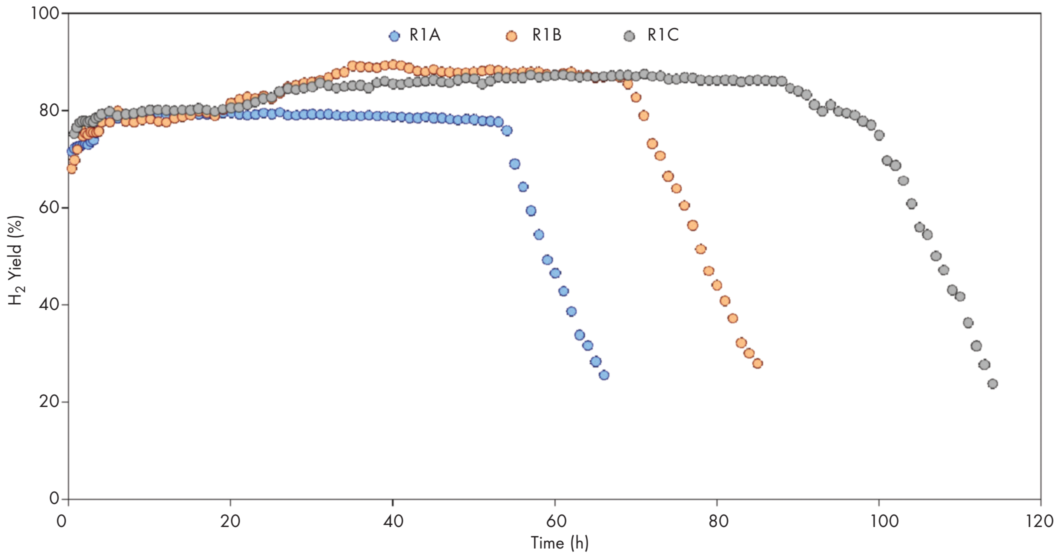

Figure 3. **Catalytic performance measured in terms of hydrogen yield by three different catalysts.**

lations increases with increase in temperature. Thus, in the range of 500-800°C, the best results were obtained at 800°C. The sulfur capture capacity increases considerably upon coating the desulfurizer on 1 x 9 inch corrugated stainless steel foils to enhance the surface area.

The time dependence of sulfur capture by the clinoptilolite-based (C-series) and diatomite-based (D-series) sorbents on the foils during long-term (approximately 350h) exposure to a stream containing 3000 ppm H_2S is shown in Figure 2. As can be seen, no breakthrough (in terms of sulfur signal shown by the flame photometric detector (FPD) of the GC) was observed with either sorbent, up to 200h on stream. In order to induce breakthrough, the flow rate was doubled after 250h on stream in the case of D3. Saturation of the sorbent sets in after the 347th hour on stream, as can be seen from the rise in H_2S signal in GC at the end of this period.

Sulfur-Tolerant Reforming Catalysts

Catalysts were made by dispersing noble metals onto the ten mole percent gadolinia-doped ceria (GDC) support material. The catalysts were characterized by a host of analytical techniques with respect to their structural, morphological, chemical and thermal qualities. The performance of three catalysts was evaluated by measuring the hydrogen yield from the steam reforming of kerosene at 800°C. A sample graph is shown in Figure 3.

Since these reformates originate from kerosene that contains 260 ppm of sulfur, it is important to study the difference in performance of these three catalysts in terms of their sulfur tolerance. For this purpose, the sulfur levels in the exit stream was also followed online during the reforming experiments. The concentration of H_2S as a function of the progress of the reaction is shown in Figure 4.

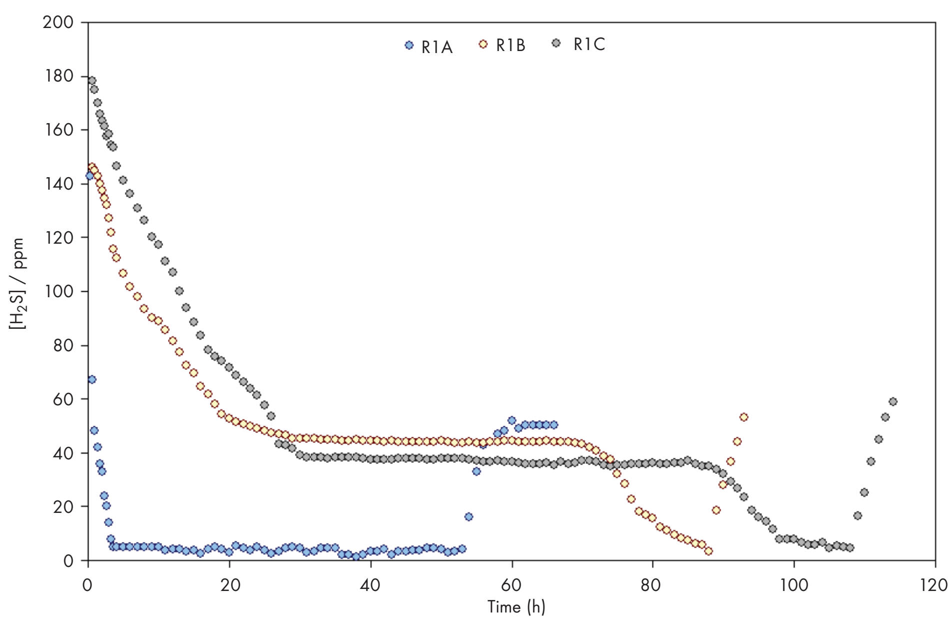

Figure 4. **Trend in H_2S concentration in the exit stream with different catalysts.**

The stability trend with respect to sulfur tolerance observed in Figure 4 is complimentary to that seen in Figure 3 in terms of hydrogen yield. For example, the sulfur level (in terms of H_2S) drops rather quickly in the early stage of reformation, during which the hydrogen yield is somewhat lower, signifying that a steady-state has not yet been reached. Beyond this, the concentration of sulfur is somewhat constant; this is seen as the active phase of the catalyst where the hydrogen yield is stable and high for an extended period. Once the active noble metal sites get completely sulfided, deactivation via sulfur poisoning ensues and the hydrogen yield begins to decrease.

SUMMARY

The initial results yielded from this study were very encouraging: nanoscale-doped-ceria proved a good candidate support material in the development of novel sulfur-tolerant catalyst formulations. It was found that all formulations evaluated exhibited sulfur-tolerance without significant reduction in active surface area (a measure of catalytic performance). Steam-reforming experiments with kerosene (JP-8 surrogate) yielded a reformate rich in hydrogen and significantly reduced sulfur content. Several desulfurizer formulations were synthesized on clinoptilolite and diatomaceous earth support matrices, which showed excellent performance at various temperatures between 500 and 800°C. The results of this study would suggest that a combination of an agile desulfurizer formulation with an optimal sulfur-tolerant nanocatalyst would provide an ideal combination to obtain a ready-to-use, sulfur-free, hydrogen-rich feed for SOFCs from a variety of logistic fuels.

NOTE & REFERENCES

* A *catalyst* is a material that, when present, will facilitate or in most cases accelerate the reaction rate of the chemical species in a reactor. A catalyst is not a reactant and thus is not consumed in the reaction. Catalysts work because their surfaces attract the various reactant molecules, which then combine more easily by their proximity to one another on the surface. Once the reaction is completed, the product molecule typically releases from the catalyst. In an automobile's catalytic converter, for example, the unconsumed hydrocarbons, carbon monoxide and nitrogen oxides in the exhaust are allowed to run over a noble metal (platinum or palladium) catalyzed monolithic bed, which instantly converts these species into carbon dioxide, water and nitrogen molecules.

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Materials and Manufacturing Challenges of Direct Methanol Fuel Cells

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INTRODUCTION

Fuel cells are attractive power sources for a variety of Department of Defense (DoD) needs. Among the various types of fuel cells, direct methanol fuel cells (DMFC) are particularly well-suited for mobile applications (such as soldier power, unmanned underwater systems, and communication devices) since DMFCs employ easily manageable liquid methanol fuel with excellent energy storage densities. The use of DMFCs for portable devices will eliminate the lengthy recharging process required for lithium ion (Li-ion) batteries (using an electrical outlet).[1] DMFCs provide uninterrupted, continuous power as long as the methanol fuel is supplied since they are energy conversion devices rather than energy storage devices, such as batteries. Moreover, DMFCs provide a much higher energy density than Li-ion batteries. Theoretically, methanol offers a volumetric energy density and a gravimetric (weight) energy density that is ten and 30 times higher, respectively, than Li-ion batteries. However, in practice the energy density of DMFCs will be lower than the theoretical value due to their lower efficiency (approximately 30 %). Nevertheless, use of a DMFC can reduce the weight of the power supply by 50% when running a 20 watt (W) laptop for 24 hours. The reduction in power supply weight increases as the system size increases due to the decoupling of power delivery from energy storage. For example, a DMFC can reduce the weight of power sources soldiers need to carry by up to 65% over a 72-hour mission.[2]

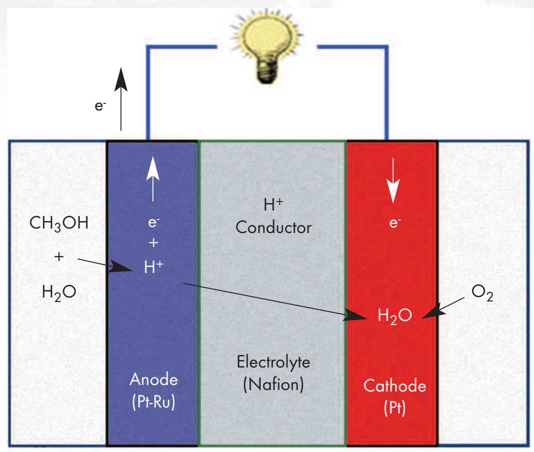

Figure 1. Operating principles of a direct methanol fuel cell (DMFC).

However, the adoption of DMFC technology has been hampered by high system costs and complexity, low operating voltage and efficiency, and durability issues.[1] Several of these problems are directly linked to materials, manufacturing, and system challenges. This article focuses on the materials and manufacturing challenges and the development of new materials to overcome these technical problems, thus making DMFC technology viable for the DoD and consumer applications.

DIRECT METHANOL FUEL CELLS

The principles involved in the operation of a direct methanol fuel cell are shown in Figure 1. A DMFC consists of an anode, a cathode, and a proton-conducting electrolyte membrane, which are collectively called a membrane-electrode assembly (MEA). Conventionally, the anode and cathode catalysts are, respectively, nanostructured platinum-ruthenium (Pt-Ru) and Pt particles (approximately 3 nm) dispersed in a conductive carbon support. The proton-conducting electrolyte normally employed is a polymeric membrane called Nafion®,* which is a hydrated perfluorosulfonic acid polymer (see Figure 2). During the cell operation, protons are produced by an oxidation of methanol fuel with the assistance of the Pt-Ru electrocatalyst at the anode. The produced protons migrate from the anode into the cathode through the Nafion membrane, while the electrons produced during the oxidation reaction flow from the anode to the cathode through the external circuit, as indicated in Figure 1. The electrons and protons react with the diatomic oxygen molecules at the cathode with the assistance of the Pt electrocatalyst to produce water as the byproduct. The relevant chemical reactions occurring at the anode and cathode as well as the overall cell reaction are given in Figure 3. The free energy change, ΔG, involved with the overall chemical reaction is tapped out as useful electrical energy in accordance with the relation below:

$$\Delta G = -nFE \tag{1}$$

where n is the number of electrons involved in the chemical reaction, F is the Faraday constant (96,487 coulombs per mole), and E is the cell voltage. The single cells similar to the one shown in Figure 1 are stacked together with carbon bipolar plates to obtain a fuel cell stack which can provide the desired voltage and power.

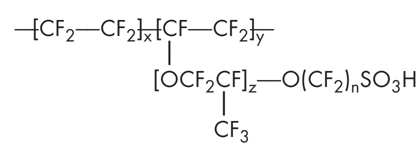

Figure 2. Chemical structure of the polymeric membrane Nafion.

MATERIALS CHALLENGES

The performance and commercialization of DMFCs is, however, hampered by problems associated with the polymeric Nafion membrane, Pt and Pt-Ru electrocatalysts, and carbon support. The materials challenges are briefly outlined in this section.

The use of Nafion as a membrane in DMFC presents several difficulties.[3] First, it is expensive. Second, Nafion allows permeation of methanol fuel from the anode to the cathode, generally referred to as *methanol crossover*. This is important because oxidation of the permeated methanol on the cathode Pt electrocatalyst leads to mixed potentials at the cathode, resulting in voltage loss. The methanol permeation also results in a waste of fuel and con-

Reaction at the anode:
$CH_3OH + H_2O \rightarrow 6H^+ + CO_2 + 6e^-$

Reaction at the cathode:
$4H^+ + 4e^- + O_2 \rightarrow 2H_2O$

Overall cell reaction:
$CH_3OH + H_2O + 1\frac{1}{2}\, O_2 \rightarrow 3H_2O + CO_2$

Figure 3. **Chemical reactions involved in a direct methanol fuel cell (DMFC).**

sequently a reduction in energy density. To reduce methanol crossover, thicker membranes like Nafion-117 (175 µm thick) are often preferred for DMFC. This offers an increase in ionic resistance and a decrease in power density.

Methanol permeability and crossover occur due to the structure of the Nafion membrane. Nafion consists of hydrophobic main chains and hydrophilic side chains containing ionic sulfonic acid ($-SO_3H$) groups, as shown in Figure 2. The sulfonic acid groups cluster together to form ionic channels, as illustrated in Figure 4. While the flow of water through the ionic channels helps to carry the protons (vehicle mechanism of proton conduction) and offers high proton conductivity, it also leads to a flow of methanol from the anode to the cathode. The formation of wider ionic channels facilitated by the aliphatic polymeric structure of Nafion leads to a high crossover of methanol from the anode to the cathode. Moreover, the Nafion fluoropolymer membrane is prone to attack by peroxide and superoxide intermediates formed during the oxygen reduction reaction. These drawbacks have generated immense interest in the development of alternative membranes for DMFCs.

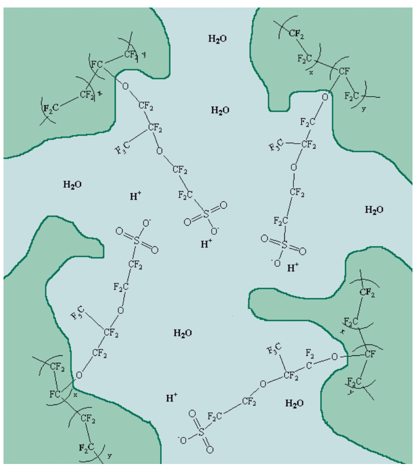

Figure 4. **Formation of ionic channels by a clustering of the sulfonic acid groups in a polymeric Nafion membrane.**

As shown in Figure 3, the methanol oxidation reaction involves a six-electron process, while the oxygen reduction reaction involves a four-electron process. The higher energy required to break the carbon-hydrogen bonds and the six-electron process make the methanol oxidation reaction sluggish even with the best known Pt-Ru electrocatalyst. Similarly, the difficulty in breaking the double bonds of the diatomic oxygen molecule and the four-electron process make the oxygen reduction reaction also slow even with the best known electrocatalyst (Pt). Both the sluggish methanol oxidation and oxygen reduction reactions lead to a significant drop in the cell voltage of a DMFC under the operating conditions. The oxygen reduction reaction is a common process for both DMFCs and proton exchange membrane fuel cells (PEMFCs) operating with hydrogen fuel. However, the much slower oxidation of methanol in DMFCs, compared to that of hydrogen in PEMFCs, together with a poisoning of the cathode Pt electrocatalyst† results in a low operating voltage for a DMFC compared to that of a PEMFC.

Although Pt is used for the oxidation of hydrogen fuel in a PEMFC, Pt-Ru rather than Pt is used to oxidize methanol fuel in a DMFC. The addition of Ru oxidizes the carbon monoxide (CO) intermediate formed during the methanol oxidation reaction to carbon dioxide (CO_2) through the formation of hydroxyl groups.[4] However, the use of Pt-Ru brings additional difficulties, since Ru tends to migrate as a dissolved species from the anode to the cathode through the Nafion membrane. The gradual depletion of Ru at the anode during DMFC operation leads to a decrease in the kinetics of the already slow methanol oxidation reaction and consequent performance loss. Also, the electrocatalysts at the cathode and anode tend to dissolve and reform, resulting in an increase in particle size and consequent decrease in electrocatalytic activity and performance during cell operation.[5]

The electrocatalysts are normally employed as supported catalysts, (i.e. the electrocatalysts are dispersed in a conductive carbon support) and the carbon-supported Pt-Ru/C and Pt/C electrocatalysts are employed, respectively, as anode and cathode in a DMFC. While the electrolyte membrane should support only ionic (proton) conduction without any electronic conduction, the anode and cathode should support both proton and electron conduction to allow the flow of protons and electrons. The mixed ionic-electronic conduction in the electrodes is generally achieved by adding an adequate amount of the ionomer Nafion into the carbon-supported anode and cathode structures. The dispersion and distribution of the electrocatalysts and the ionomer in the conductive carbon support are critical to efficiently utilize the expensive Pt-based electrocatalysts. Any electrocatalyst nanoparticles trapped in the micropores of the carbon support cannot be accessed by the methanol fuel or the oxygen oxidant. Approximately 70% of the electrocatalysts in the electrode structure often become unutilized, resulting in a waste of the expensive electrocatalysts. Moreover, the porous carbon structure is prone to corrosion and degradation under the operating conditions of temperature and potential, which causes performance loss during long-term operation.

Some of the critical materials challenges that are discussed above are summarized here:

- High cost of Nafion membrane and Pt-based electrocatalysts
- High methanol permeability and crossover of methanol through the Nafion membrane
- Degradation of Nafion membrane by peroxide and superoxide intermediates formed during reaction
- Sluggish methanol oxidation reaction on the Pt-Ru electrocatalyst
- Sluggish oxygen reduction reaction on the Pt electrocatalyst
- Dissolution and growth of the electrocatalyst particles during cell operation
- Poisoning of the cathode Pt electrocatalyst by the permeated methanol
- Trapping of electrocatalysts in the micropores of carbon and their resultant poor utilization
- Chemical instability and corrosion of the carbon support

These critical challenges have created enormous interest in the development of alternate membranes, electrocatalysts, and conductive supports for DMFCs. Accordingly, a brief overview of the development of new membranes and electrocatalysts that can overcome some of the problems is presented below.

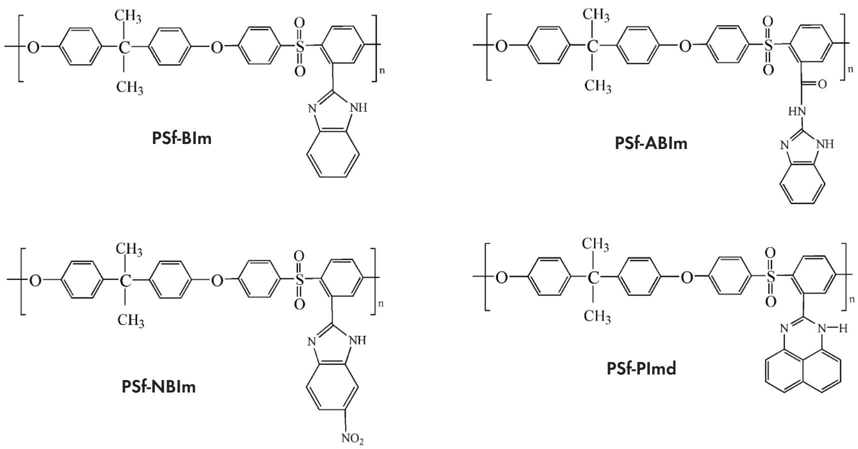

Figure 5. **Structures of various N-heterocycles tethered to basic aromatic polymers.**

NEW MATERIALS DEVELOPMENT

Membranes

With a given membrane thickness, aromatic polymers such as sulfonated poly(ether ether ketone) (SPEEK) and sulfonated poly(sulfone) (SPSf) are known to exhibit lower methanol crossover than Nafion.[6-8] The lower methanol crossover is due to narrower ionic channels compared to that in Nafion as indicated by small angle X-ray scattering.[9] While the flexible aliphatic chains facilitate the formation of wider ionic channels in Nafion, the less flexible aromatic backbones in SPEEK and SPSf lead to narrower ionic channels. However, SPEEK and SPSf membranes exhibit lower proton conductivity than Nafion. In recent years research has been focusing on blend membranes consisting of an acidic polymer and a basic polymer which have similar aromatic backbones.[10-14] The approach involves the tethering of an N-heterocycle group to an aromatic polymer like poly(sulfone) (PSf) or poly(ether ether ketone) (PEEK) to obtain a basic polymer, followed by its blending with an aromatic acidic polymer such as SPEEK or SPSf. Figure 5 shows four basic polymers in which benzimidazole (BIm), aminobenzimidazole (ABIm), nitrobenzimidazole (NBIm), and perimidine (PImd) have been tethered to PSf to give, respectively, PSf-BIm, PSf-ABIm, PSf-NBIm, and PSf-PImd. In a blend membrane consisting of one of these basic polymers and the acidic polymer SPEEK, the acid-base interaction between the nitrogen atoms of the basic polymer and the sulfonic acid groups of the acidic polymer provides proton conduction via a Grotthuss-type (hopping of protons) mechanism, as illustrated in Figure 6. This is in addition to the vehicle mechanism that occurs between the sulfonic acid groups of the acidic polymer utilizing water as a proton transport medium similar to that in Nafion. Due to the occurrence of both vehicle and Grotthuss-type mechanisms, these blend membranes exhibit higher proton conductivity than the acidic polymer SPEEK itself (Table 1) at optimum acidic to basic polymer ratios.

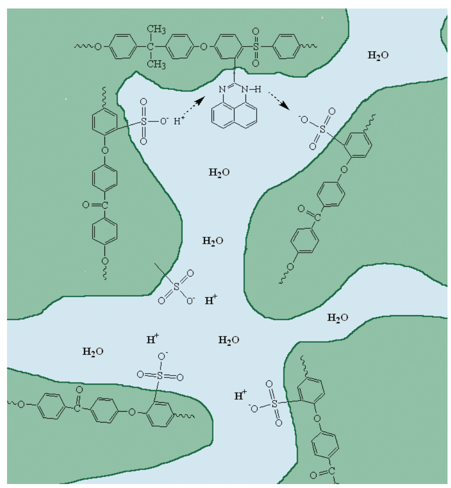

Figure 6. **Formation of ionic channels by a clustering of the sulfonic acid groups and an insertion of the basic N-heterocycle groups into the ionic channels due to acid-base interaction in the blend membranes.**

Although the conductivity values of the blend membranes are still lower than that of Nafion, the blend membranes with a thickness of approximately 60 µm exhibit significantly lower methanol crossover than Nafion-115 (125 µm thick) and SPEEK (approximately 60 µm thick) membranes, as displayed in Table 1. The methanol crossover value of Nafion-117 is similar to those of the blend membranes, but the much thicker (175 µm) Nafion-117 membrane will encounter higher ionic resistance. As a result, the blend membranes exhibit lower voltage loss and higher power density than Nafion-115, Nafion-117, and SPEEK membranes (Figure 7 and Table 1). In

Table 1. **Comparison of the open-circuit voltage (OCV), proton conductivity at 65°C and 100% relative humidity, maximum power density, and methanol crossover current density of Nafion-115 (125 µm thick), Nafion-117 (175 µm thick), plain SPEEK (approximately 60 µm thick), and blend membranes with different basic polymers (approximately 60 µm thick). The cell temperature is 65°C and the methanol feed concentration is 1 mol/dm³.**

Membrane	OCV (V)	Maximum power density (mW/cm^2)	Methanol crossover current density (mA/cm^2)	Proton conductivity (mS/cm)
Nafion-115	0.63	59	122	143
Nafion-117	0.71	49	86	143
SPEEK	0.69	64	115	69
SPEEK/PSf-ABIm	0.71	95	95	94
SPEEK/PSf-NBIm	0.73	84	87	87
SPEEK/PSf-BIm	0.72	73	91	79
SPEEK/PSf-PImd	0.74	73	77	73

fact, the lower methanol crossover of the blend membranes enables us to work with much thinner membranes compared to Nafion-115 and Nafion-117, which helps to overcome the lower proton conductivity limitations of the SPEEK or the blend membranes.

As shown in Table 1, the lower methanol crossover with the blend membranes is reflected in higher open-circuit voltages (OCV) compared to those found with SPEEK and Nafion-115 membranes. The lower methanol crossover can also allow operation of DMFCs with higher concentrations of methanol, offering the possibility to enhance the energy density of practical DMFC systems.[13] The lower methanol crossover of the SPEEK membrane compared to that of Nafion-115 membrane is due to the narrower ionic channels as pointed out earlier.[6-9] The lower methanol crossover of the blend membranes compared to that of SPEEK membrane itself is due to the insertion of the N-heterocycle groups into the ionic cluster, as shown in Figure 6. This was confirmed by small angle X-ray scattering studies. Both the lower methanol crossover and the enhanced proton conductivity lead to a better performance for the blend membranes compared to the conventional SPEEK membrane with the same thickness (approximately 60 µm).

The blend membrane strategy presented here has the potential to improve the performance further by optimizing the pKa value difference between the acidic and basic polymers as well as by tethering different N-heterocycles in the basic polymer. One critical issue with these new membranes is to employ a compatible ionomer in the electrocatalysts layer and thereby minimize the interfacial resistance between the membrane and electrocatalyst layers. Accordingly, the membrane-electrode assemblies fabricated with the blend membranes and SPEEK ionomer in the catalyst layer offer better performance than MEAs fabricated with the blend membranes and Nafion ionomer.[15]

In addition to offering attractive performance in DMFCs, these blend membranes are inexpensive compared to the fluoropolymer Nafion. The components in the blend membranes are also known to exhibit excellent chemical, thermal, and mechanical stabilities. With lower cost and interesting performance, the blend membranes described here offer great promise for DMFC applications.

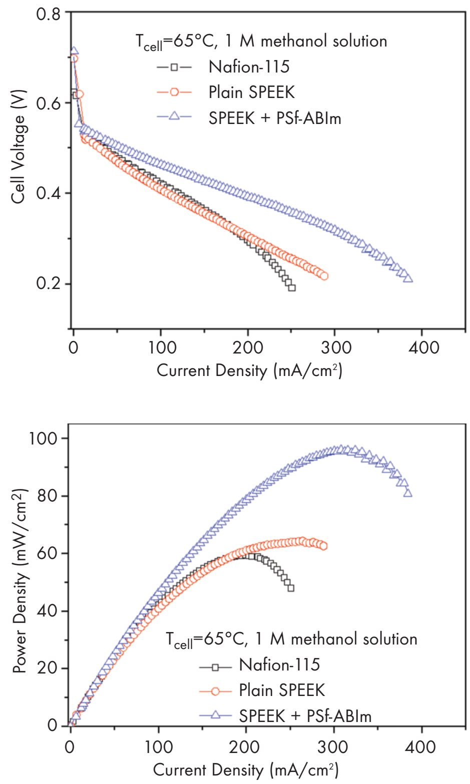

Figure 7. **Comparison of the polarization curves and power densities of the blend membrane consisting of acidic SPEEK and basic PSf-ABIm polymers with those of Nafion-115 and SPEEK membranes.**

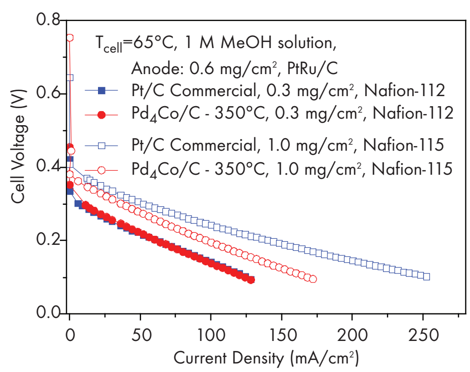

Figure 8. **Comparison of the electrocatalytic activities of commercial Pt/C and 350°C annealed Pd_4Co/C for the oxygen reduction reaction with Nafion-112 and -115 membranes and different catalyst loadings.**

Electrocatalysts

As pointed out earlier, carbon-supported Pt-Ru and Pt (designated as Pt-Ru/C and Pt/C) are the best known electrocatalysts, respectively, for the methanol oxidation and oxygen reduction reactions. Recent research at the University of Texas at Austin has been focusing on Pd-based electrocatalysts for the oxygen reduction reaction. The oxygen reduction reaction involves the adsorption of O_2 molecules on the electrocatalyst, followed by a cleaving of the O-O bond and reduction of the metal oxide with H^+ ions to produce water (see cathode reaction in Figure 3). With this perspective, alloying of a metal like palladium (Pd), which has high positive electrochemical reduction potential, E°, with another metal like cobalt (Co), which has high negative free energy change ΔG for oxide formation, has been considered to offer high electrocatalytic activity for the oxygen reduction reaction.[16] Accordingly, several Pd-based alloys such as Pd-Co, palladium-molybdenum (Pd-Mo), and palladium-tungsten (Pd-W) have been explored as electrocatalysts for oxygen reduction reaction.[17-21] The incorporation of Co, Mo, and W with high negative ΔG for oxide formation into Pd invariably enhances the electrocatalytic activity. More importantly, alloying of Pd with other metals increases the chemical stability and durability and inhibits the particle growth on annealing at higher temperatures.[19-21]

The Pd-based alloys exhibit much higher tolerance to methanol than Pt. This offers an important advantage in DMFCs as the Pd-based electrocatalysts will be poisoned to a lesser extent than Pt by the methanol that permeates from the anode to the cathode through the membrane, and thereby minimizing the voltage or performance loss. Figure 8 compares the performances of commercial Pt/C and Pd_4Co/C electrocatalysts for the oxygen reduction reaction. With a thicker Nafion-115 membrane (125 µm thick) and high catalyst loading (1.0 mg/cm^2), commercial Pt/C exhibits higher catalytic activity (or lower voltage loss) than Pd_4Co/C, while with a thinner Nafion-112 membrane (50 µm thick) and a low catalyst loading (0.3 mg/cm^2), Pd_4Co/C exhibits performance similar to that of commercial Pt/C. Although the intrinsic catalytic activity of Pd_4Co is lower than that of Pt, when the methanol crossover is high with the thinner Nafion-112 membrane and the catalyst loading is low, a higher poisoning effect of the Pt electrocatalyst by methanol compared to that of Pd_4Co brings down the performance of Pt similar to that of Pd_4Co. The higher tolerance of Pd-based electrocatalysts to methanol can thus help to lower the cathode catalyst loading and to operate DMFCs with higher concentrations of methanol, offering cost savings and increase in overall energy density. Moreover, the cost of Pd is approximately 25% of the cost of Pt, and the replacement of Pt-based electrocatalysts by Pd-based electrocatalysts will lower the overall system cost as a significant portion of the DMFC system cost is due to the electrocatalysts.

While Pt itself is a poor electrocatalyst for methanol oxidation, addition of hydrophilic Ru that facilitates the formation of hydroxyl groups provides good catalytic activity, although the migration of Ru from the anode to the cathode is a serious problem. Similarly, addition of other hydrophilic elements such as tin (Sn) to Pt is also known to enhance the catalytic activity for methanol oxidation. While replacement of Ru by Sn can lower the cost to some extent, replacement of Pt by other less expensive metals is desirable. Explorative research could lead to the identification of potentially low cost electrocatalysts for the methanol oxidation reaction.

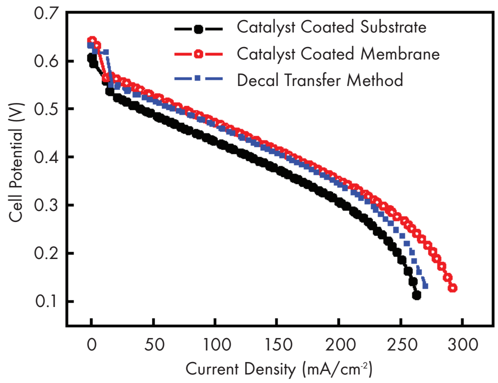

Figure 9. Comparison of the performances of MEAs fabricated by different methods.

As pointed out earlier, carbon corrosion under the operating conditions of DMFCs is another issue. In this regard, replacement of carbon by other conductive oxide supports may prove to be useful. Also, supporting the metal or alloy electrocatalysts on oxides could enhance the methanol oxidation kinetics by facilitating the oxidation of the CO intermediate to CO_2. Oxide supports are being increasingly explored in recent years, and they may prove to be a viable approach to overcome the carbon corrosion problem.

MANUFACTURING CHALLENGES

The membrane-electrode assembly is a key component of a DMFC. The performance of DMFCs is highly dependent on the MEA fabrication process. There are two major MEA manufacturing processes: (1) catalyst coated substrate (CCS) method and (2) catalyst coated membrane (CCM) method.[22] In the CCS method, the catalyst layer is directly coated on the top of the substrate (such as carbon paper or carbon cloth containing the gas diffusion layer (GDL)) and then hot pressed with the membrane. In the CCM method, the catalyst is coated on the membrane and then hot pressed with the carbon cloth or carbon paper containing GDL. There are two approaches with the CCM method: (1) direct catalyst coating on the membrane (hereafter referred to as CCM) and (2) a decal transfer method (DTM).[23] However, the DTM method needs an additional transfer step, so the direct catalyst coating (CCM) on the membrane is the efficient and simple process for the continuous manufacturing of MEAs. Figure 9 compares the performances of MEAs fabricated by the CCS, CCM, and DTM methods. The CCM process offers better performance than the CCS method. Also, when the catalyst is coated on the porous substrate, a significant amount of catalyst is wasted due to the permeation of the electrocatalyst nanoparticles into the porous substrate. Thus, both from a performance and continuous manufacturing points of view, the CCM method is preferred.

However, the CCM process is complicated by the swelling of the membrane when the membrane is hydrated during the direct coating process.[24] The hydration process induces in-plane compression in the friable membrane, and the membrane creeps to relieve these stresses. To achieve stable direct coating on the membrane, the swelling problems should be controlled. Approaches with pre-swelled membranes in our laboratory appear promising, and they may prove useful to overcome this problem.

Several techniques can be employed for coating the catalyst.[25] For example, spraying, painting, and doctor blade methods are all used successfully. However, factors like coating time, reproducibility, consistency, and controllability need to be considered for continuous coating processes. Also, the procedures for the preparation of the catalyst ink slurry play an important role in controlling the particle size, surface morphology, composition, and electrocatalytic activity with direct consequences on the fuel cell performance.[26] It is important to avoid the growth of the electrocatalyst nanoparticles during the electrode fabrication procedure. Specific organic solvents and optimized procedures should be used to achieve a high degree of dispersion and to prevent particle growth during the electrode preparation processes.

In addition to MEAs, other components like the bipolar plates serving as current collectors play a key role in the performance of DMFCs. Graphite is generally used for bipolar plates. The graphite bipolar plates with flow channels/fields for liquid methanol and oxygen/air feed are currently fabricated by machining, which is slow and expensive. Development of alternative manufacturing processes, such as freeform fabrication methodologies, may not only increase the production rate but could also allow the design of complex and more efficient flow fields which can enhance power density.

CONCLUSIONS

Direct methanol fuel cells are appealing as a power source for a variety of DoD applications. However, their adoption is hampered by high cost, durability, and performance issues, which are linked to severe materials, manufacturing, and system challenges. Development of low-cost, more efficient materials, novel manufacturing processes, and innovative system design can enhance their commercialization prospects for DoD and consumer applications.

Design and development of new membrane materials based on aromatic polymers not only lower the membrane cost but also minimize some of the persistent problems such as methanol crossover. For example, blend membranes based on an acidic aromatic polymer and a basic aromatic polymer are found to exhibit lower methanol crossover and higher power density than Nafion-115 membrane, while lowering the cost. Similarly, Pd-based alloys with a high tolerance to methanol are found to be promising for the oxygen reduction reaction. Despite the lower intrinsic catalytic activity compared to that of Pt, the higher tolerance to methanol makes the Pd-based electrocatalysts competitive with Pt, while also allowing potentially a lower cathode catalyst loading. The cost of Pd is approximately 25% of the cost of Pt, and the replacement of Pt by Pd-based alloys can lower the DMFC cost significantly. Coupling of the new blend membranes that have suppressed methanol crossover with the Pd-based alloy electrocatalysts which have high tolerance to methanol could further reduce the problems of methanol crossover. Such a system could also allow operation with higher concentrations of methanol, offering the potential to increase the energy density compared to that achieved with Nafion and Pt-based electrocatalysts. Discovery of new low-cost, more efficient electrocatalysts for methanol oxidation could offer further gains.

Reproducible, cost-effective, continuous manufacturing of membrane-electrode assemblies is also critical for a viable commercialization of the DMFC technology. Catalyst coated membrane approach offers advantages over other methods, but the membrane swelling issue during the process needs to be addressed. Similarly, novel manufacturing approaches to fabricate bipolar plates with optimum flow fields can enhance the performance. Finally, efficient integration of the various components with adequate controls is critical to realize a DMFC system with reliable performance.

ACKNOWLEDGEMENTS

Financial support by the Office of Naval Research MURI grant No. N00014-07-1-0758 is gratefully acknowledged. The author also thanks Mr. Wen Li and Dr. In-Su Park for their assistance with the data and figures.

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* Nafion is a registered trademark of E. I. du Pont de Nemours and Company, Corporation.

† The Pt electrocatalyst is poisoned by the methanol that permeates from the anode to the cathode through the Nafion membrane.

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Compact Superconducting Power Systems for Airborne Applications

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INTRODUCTION

In the development of future airborne megawatt-class power generation, it is important to minimize both the size and the weight of the system. The primary means of increasing the power density within the generator, as for all rotating machinery such as motors and alternators, is to maximize the magnetic flux density. This can be achieved by using a higher current-carrying capacity wire to increase the ampere-turns* in the windings without adding more turns via a longer length of wire. This has already been accomplished through the incorporation of superconducting wire in magnetic resonance imaging (MRI) magnets used in the medical field. In the case of MRI devices, the large size of the magnet is necessary to allow space for a human to fit inside. Without the availability of superconductors, MRI devices would require an extremely large magnet and a large room with a high ceiling. Another beneficial effect of incorporating superconductors into power systems is to increase the overall operation efficiency, thereby lowering parasitic heat losses, which can become substantial for higher power systems.

> A **superconductor** is a material which, when cooled to less than a critical temperature, loses all electrical resistance.

A common misconception is that superconductor usage requires large amounts of cryogenic fluids in complicated coolant systems. Advancements in refrigeration systems eliminate this need, allowing for the use of more compact, higher-efficiency cryo-coolers. The cooling needs of a cryogenic system depend on the design of the system and, in particular, the heat losses of the insulation components and electrical devices. Cryogenic cooling is not a problem for most superconductor systems and should be considered the norm rather than the exception. Also, the reliability of the latest generation of cryo-coolers, which include new flexure mechanical bearings, is so high that the failure rates cannot even be measured after 5-10 years of operation. In addition to cryogenic systems, a new class of superconducting wire became available in 2008. The newer, high-temperature superconducting (HTS) wire, made from an yttrium barium copper oxide ($YBa_2Cu_3O_{7-Z}$ or YBCO) coated conductor, typically takes the form of a thin, flat tape, as opposed to a round wire. Two US companies† produce this new superconducting wire. The YBCO wire allows a much higher operating temperature than the previous generations of superconducting wire made from the bismuth strontium calcium copper oxide ($Bi_2Sr_2Ca_2Cu_3O_{10-Z}$ or BSCCO) family, thereby requiring a significantly smaller cryo-cooler to function. Depending on the magnetic field of the application, the operational temperature of YBCO is typically 20-40 K higher than for BSCCO wires.

There are several specific high-power applications being developed by the Air Force. These are described in the following sections.

MEGAWATT AIRBORNE GENERATOR

Recent efforts by the US Air Force (USAF) have been advancing power technologies using superconductors for airborne high-power applications (HPA). Large onboard demands for electrical power are projected for future military aircraft, making it necessary to develop not only suitable power generators but power distributors and conditioning technologies as well. To that end, the USAF initiated a new program for a Megawatt-level Electric Power System (MEPS) to develop and test superconducting power systems for airborne HPA. In 2004, the Air Force Research Laboratory (AFRL) initiated the design, building, and testing of the MEPS. The objective for the MEPS generator was to demonstrate HTS machine designs yielding power ratios in excess of the Air Force's initial (conservative) goal of 4.0 kW/lb (8.82 kW/kg). Using this figure as a starting point, future systems could be driven to much higher power ratios, since the initial machine configuration was a homopolar inductor alternator‡ (HIA). A prototype one-megawatt generator was completed in early 2007 and then a battery of tests were conducted to ensure a successful first full-power run of

Superconducting Generator MEPS Program

the HTS machine. During testing, the generator produced 1.3 MW output at its design speed of 10,000 rpm (10 krpm) and achieved 97% overall efficiency, even taking into account cryo-cooler losses. The MEPS demonstration validated the HIA concept as one viable alternative not only for HTS machines but also for a variety of advanced technologies for future HTS machine designs using the newer YBCO superconducting wire. The program included a conceptual design for a five MW HIA baselined to meet the above-noted specific power ratio goal.

GYROTRON MAGNET

Another superconductor candidate for HPA is the gyrotron magnet. A gyrotron is a high-field magnet necessary to generate high-power electromagnetic radiation. Similar to the MRI magnet, this can be accomplished with superconducting wire, but uses older, low-temperature superconductors (LTS). Developing an HTS magnet with the newer HTS wire to replace the LTS windings could substantially reduce the refrigeration load. The new YBCO conductor operates at 60-77 K (as opposed to 4.2 K for LTS wire) and requires a cryo-cooler that is more than an order of magnitude smaller (by output) than that used for LTS materials. One company has already made an HTS gyrotron magnet out of an HTS conductor, they currently have a program to make a prototype YBCO gyrotron magnet.§

HTS Gyrotron

COMPACT POWER CABLES

With the development in the past 20 years of new electric conductors having up to 200 times higher power/volume capacity than standard copper conductors, the potential now exists to use these new conductors to improve the performance and efficiency of high-power current transmission systems. These new materials with higher conductivity include doped carbon graphite or nanotubes, hyperconducting metal alloys (e.g., aluminum) or BSCCO, and YBCO superconductor wires with operational temperatures up to 80 K.

The development of improved power density devices for specialized applications (including airborne applications) is ongoing; however, electrical power transmission between these devices is a problem that merits further investigation. For example, the weight of power cables running from advanced airborne high-power generators is likely to exceed the generator weight; and heat losses of wires, which are proportional to the increased device power levels, can reduce system performance. Improving the high power device operational temperatures from 50 K to 300 K would lead to the design of more optimal power transmission devices, further reducing system heat loss and weight. While there is significant focus on the development of higher performance power transmission devices for commercial power industries, there is relatively little activity ongoing to optimize power transmission systems for low voltage operation and low AC frequency or DC systems for airborne applications. Previously developed superconducting power lines for high voltage, high power operation (20-120 kV, 100-1500 MW) yielded four- to forty-fold reductions in total system heat loss (including cryogenic), and similarly transmission cable size and weight were reduced by a factor of ten, compared to copper, for commercially viable systems. Unfortunately, similar studies for airborne systems have thus far been very limited.

The basic principles required to design electrical power transmission systems for airborne applications are well understood; however, their specific design criteria have not yet been considered in detail. For airborne applications, operating voltages are typically fixed at 270 volts to minimize arc discharges at lower atmospheric pressures. However, this also causes problems with power supplies and power electronics. The output or operating power of a device is known from basic principles, specifically Ohm's law ($P = IV$, where I is the applied current, and V is the operating voltage). Thus, it is not practical to increase the operating voltage to increase the power output substantially for airborne applications, as would be typical for ground-based transmission systems. Consequently, it would only be practical to increase the operating current. Since voltage will not be increased, the device design may benefit by reducing the amount of electrical insulation needed. However, this also creates new design problems because of the need to accommodate much higher current levels.

A first study of this problem considered the design of high power transmission lines and cryogenic current leads for low voltage (<300 V) and DC, low-frequency AC (<1000 Hz), as well as for short line lengths (30 meters or less) which are typical for airborne applications. For any high-power application, developing refrigerated (or cryogenic) power transmission systems is considered when system size, weight, and total power losses, (including refrigeration) are projected to be lower than equivalent solid state components or materials (such as copper or aluminum) which operate at room temperature. An early study of transmission systems (using a 10-meter line at 5-10 MW DC power) demonstrated that by using a high-temperature superconductor system (HTS) instead of copper wire, transmission power densities could be increased three- to ten-fold, and the system heat loss and weight could be reduced by 10-15 kW and 1500-3000 lbs., respectively. The reason for the dramatic weight and heat loss differences between the superconductor and copper systems is the very high copper wire weight needed for these high power levels operating at 270 volt fixed level; and also because heat losses from the superconductor are almost zero, even for very high-power transmission. The only significant power losses for the superconductor transmission system are the cryo-cooler and vacuum component losses needed to maintain the cryogenic environment. Similarly, the cryo-cooler and vacuum components represent the only significant weight additions over conventional systems. The HTS wires experience almost no heat loss

A **hyperconductor** is a material which, when cooled to cryogenic temperature, loses most of its electrical resistance – unlike superconductors, which lose all resistance.

and are very light and compact compared to copper wires. A similar system designed for AC power transmission also showed strong improvements, but this was limited to approximately 1 MW power transmission because superconductor cable designs to minimize AC losses are currently limited to operating conditions of no more than 3500 A or approximately 1 MW.

The energy densities afforded by superconductor power transmission devices over their copper counterparts are tremendous, which demonstrates how higher current density wires can be incorporated into power systems, thus greatly reducing the size and weight required for airborne applications. Also, heat losses can be substantially reduced. It should be noted that these improvements are realized for power transmission between devices operating at 50-77 K, such as superconducting generators and gyrotron magnets, as described above. If one of the devices was to operate at room temperature, a significant number of additional high-current power leads would be required to deliver the equivalent electrical power as at 77 K. Such high-current leads experience large heat losses (approximately 200 W/kA), which would increase the cryo-cooling requirements and reduce the benefits of the overall system. However, research on current leads operating in the 50-77 K regime has been limited, thus it may be a while before these problems are surmounted.

CONCLUSION

A major issue with superconducting wire has been overcome with the recent introduction of the YBCO coated conductor. It operates at a much higher temperature than the previous generations of superconducting wire. It also has much better stability than its predecessors, the low temperature superconductors. This article covered three examples of incorporating superconducting wire into advanced development components; two of these have been built and tested successfully, but all are YBCO conductor-ready. Although additional improvements are expected for the new YBCO conductor, it is now ready for advanced demonstrations. The future looks bright in this area, as the next generation of superconductors will dispel past misconceptions about this emerging technology and provide new opportunities for technologists with the vision and drive to seize upon them.

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* An ampere-turn is the magnetomotive force of one ampere of current flowing through a closed loop of one turn.
† SuperPower, Inc., and American Superconductor Corporation
‡ Homopolar inductor alternator is an electrically symmetrical synchronous generator with a field winding that has a fixed magnetic position in relation to the conducting supports or armatures.
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Hydrogen Fuel Cells: Research Progress and Near-Term Opportunities

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INTRODUCTION

The United States faces some energy challenges that if not resolved will negatively affect our security, economy, and environment. The country depends on foreign oil for transportation, and greenhouse gases and other criteria pollutant emissions need to be reduced. There is no single solution to these critical problems; rather they require a multifaceted approach. Hydrogen, together with advanced biofuels, plug-in hybrids, and other energy efficient transportation technologies, can be an important part of a more comprehensive and balanced energy portfolio. Fuel cells are central to establishing this integrated solution. This article describes some of the benefits of hydrogen and fuel cells, as well as some of the obstacles to their implementation on a large scale. In addition, this article highlights achievements and partnerships that are moving the technology out of the lab and into practical, real-world use.

Hydrogen, an energy carrier, can be derived from abundant and diverse energy resources, including natural gas and coal (with carbon sequestration), nuclear energy, and renewable energy resources such as wind, solar, geothermal, and biomass (including waste biogas). Hydrogen production from renewable and nuclear sources and from coal-based systems with carbon sequestration results in near-zero greenhouse gas emissions. Natural gas-derived hydrogen offers a cost-competitive near-term option that results in lower carbon emissions than the production and consumption of gasoline or the operation of hybrid-electric vehicles. Hydrogen also offers a way to "store" energy from variable renewable resources such as wind and solar power.

Fuel cells are energy conversion devices that can efficiently use hydrogen to make electricity. Water and heat are the only byproducts of using a hydrogen fuel cell. In addition to producing zero carbon dioxide and near-zero greenhouse gas emissions at the point of use, fuel cells operate quietly and can be scaled to power a variety of applications including highway vehicles, specialty vehicles (e.g., forklifts and airport baggage tugs), stationary power generation units (for backup and primary power), and portable electronic equipment and auxiliary power units. They offer more than two times the efficiency of traditional combustion technologies. For vehicles, this efficiency results in a more than 50% reduction in fuel consumption when compared to a conventional vehicle that is powered by a gasoline-fueled internal combustion engine.[1] Efficiencies for stationary applications can be even greater in combined heat and power (or co-generation) applications. The expanded use of stationary fuel cells can also help to increase the reliability of the electricity grid by reducing system loads and bottlenecks. Fuel cells are an important enabling technology for the widespread use of hydrogen, and they represent a radically different approach to energy conversion that could replace conventional power generators like internal combustion engines, turbines, and batteries.

CHALLENGES

Despite the inherent benefits, there are several challenges to the widespread use of hydrogen and fuel cells. Among the greatest challenges is reducing the initial or capital equipment cost. Fuel cells and hydrogen produced from multiple energy sources must be cost-competitive with traditional technologies and fuels to succeed in the marketplace. Another technical challenge to fuel cell vehicle commercialization is onboard vehicle fuel storage. Hydrogen has a high energy content by weight but not by volume. This makes it difficult to store sufficient quantities (e.g., enough to enable the 300-mile driving range that US consumers demand) within the size and weight constraints of a passenger light duty vehicle.

Delivery infrastructure is also a challenge. Hydrogen can be delivered by truck, and there are approximately 1200 miles of hydrogen pipeline located in certain parts of the country. Unlike with gasoline, however, there is no extensive network of fueling stations or national fuel delivery infrastructure for hydrogen. For fuel cell vehicles to enter the mainstream market, consumers need a convenient place to fuel them, and there must be a cost-effective way for the fuel to be delivered to hydrogen stations.

Working with partners across the public and private sectors, the US Department of Energy (DOE) Hydrogen Program is working to overcome these challenges. This program supports basic and applied research, technology development and learning demonstrations, safety research, systems analysis, and public outreach and education activities aimed at advancing the development and use of hydrogen and fuel cell technologies for transportation as well as for stationary and portable power generation.

PROGRESS TOWARD COMMERCIALIZATION

DOE-funded research and development (R&D) has made significant progress in overcoming technical challenges to hydrogen and fuel cell technology commercialization. Accomplishments over the last six years include:

- Reduction in the projected cost of distributed hydrogen production using natural gas (assuming widespread deployment) from $5.00 to $3.00 per gallon gasoline equivalent (gge)* – a 40% reduction.[2]

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- Reduction in the projected cost of hydrogen production using renewable-based technologies (assuming widespread deployment) from $5.15 to $4.80 per gge (e.g., electrolysis and distributed reforming† of bio-derived liquids – ethanol, sugars).[3]
- Development of technologies for the production of hydrogen from coal that will enable increased efficiency, reduced cost, and improvements in hydrogen purity.
- Reduction in the projected, high-volume manufacturing cost of automotive fuel cell systems from $275/kilowatt (kW) in 2002 to $73/kW in 2008[4]‡ and improvement in the projected durability of fuel cell systems in vehicles from 950 hours in 2006 to 1900 hours in 2008.[5] (The program's targets are $30/kW and 5000-hour durability – approximately 150,000 miles of driving – which will enable fuel cells to be competitive with current gasoline internal combustion engine systems.)
- Identification of new materials that have the potential to increase hydrogen storage capacity by more than 50%,[6] and the development and demonstration of a novel "cryo-compressed" tank concept.
- Improvement in the efficiency and durability of fuel cells for distributed energy generation.

Technology Validation

Complementing the program's robust R&D effort is a technology validation component, the focal point of which is the National Hydrogen Learning Demonstration. This 50/50 government/industry cost-shared effort brings together automobile and energy companies, as well as their suppliers and other stakeholders, to evaluate light-duty fuel cell vehicles and hydrogen infrastructure in real-world operating conditions. Data collected on fuel cell durability and efficiency, vehicle range, and hydrogen cost, among other performance parameters, feeds back to the R&D program and is measured against established technical targets. The data is published as "composite data products" that provide the public, R&D community, and other stakeholders a means for understanding progress and technology readiness.

The demonstration includes 140 vehicles and 20 fueling stations to date; vehicle data has been analyzed over the course of approximately 346,000 trips, traveling nearly 2 million miles, with more than 88,000 kg of hydrogen produced or dispensed. Results have shown a vehicular fuel cell efficiency of 53-58%, vehicle range of up to 254 miles, and a projected system durability of 1977 hours (equivalent to about 59,000 miles).[7]

In addition to the National Hydrogen Learning Demonstration, other technology validation projects are demonstrating fuel cells in distributed energy applications and examining the operation of integrated, renewable-based power generation and hydrogen production technologies. These efforts involve hydrogen generation from solar, wind, and geothermal energy and include techno-economic analysis of hydrogen as an energy storage medium for variable renewables and "peak shaving."

The DOE Hydrogen Program also seeks to address non-technical barriers to hydrogen and fuel cell commercialization, including critical needs in the areas of safety, codes and standards, and education. Activities include:

- Characterizing the behavior of hydrogen and its compatibility with materials, providing valuable information to stakeholders about the safe use of hydrogen.
- Conducting R&D needed to facilitate the development of technically-sound codes and standards.
- Supporting the development and harmonization of domestic codes and standards, and coordinating the harmonization of international codes and standards.
- Providing up-to-date educational resources, including hydrogen education tools for first responders and code officials.

PRACTICAL OPERATION IN EARLY MARKETS

R&D progress has paved the way for fuel cells to enter the commercial market in applications with less stringent technical requirements than vehicles, such as portable and stationary applications and specialty vehicles. There are more than 50 commercially available fuel cell products to support these markets.[8] Accelerating their use will preserve jobs in an industry that needs high volume purchases to ramp up production, support commercialization, and enable a domestic supplier base. It will also greatly expand the growth of the green job market with new opportunities associated with manufacturing fuel cells and related hydrogen technologies, fuel cell maintenance and support systems, and hydrogen production.[9] In addition, the success of these early markets will help overcome a number of non-technical barriers that also face the broader vehicular marketplace, including the lack of reliability data in the field, the lack of user confidence, and the inherent resistance to new technologies.

Fuel Cells for Forklift Trucks and Backup Power

For specialty vehicles, such as forklift trucks, fuel cells can be a cost-competitive alternative to traditional lead-acid batteries. Batteries have a limited range, take substantial time to recharge and cool before reuse, are prone to voltage drops as power discharges, and create downtime during battery change-outs (which can take from 15 to 30 minutes in many operations). For these reasons, on a lifecycle basis, fuel cells can be cost-competitive with batteries, particularly for continuously-used forklift trucks running two or three shifts per day when multiple battery change-outs may be required. Fuel cells are eligible for a federal tax credit up to $3,000/kW,§ which reduces the initial capital requirements, and in some situations, the operations and maintenance savings associated with fuel cells can provide a financially-attractive payback. The higher cost of hydrogen, compared with conventional fuels or electricity (which also directly affects the lifecycle economics), may be mitigated by generating hydrogen on site. Like batteries, fuel cells produce no harmful emissions at the point of use, but unlike batteries, fuel cells can be rapidly refueled, thus eliminating the time and cost associated with swapping batteries. The voltage delivered by the fuel cell is constant as long as hydrogen fuel is supplied. Using fuel cell-powered forklifts can boost productivity by eliminating trips to the battery changing station; also with no chargers, battery storage, or changing areas or equipment needed, more warehouse space is available. Table 1 compares the cost of material handling equipment powered by batteries versus fuel cells over the life of the equipment.

Fuel cells have also emerged as a potentially viable option for backup power, particularly in the telecommunications sector. Traditional backup power technologies include batteries and

Table1. **Lifecycle cost estimates of battery-powered and fuel cell-powered material handling equipment.**

	Pallet Trucks (3 kW Power System)		
	Battery-Powered (2 batteries per truck)	PEM Fuel Cell-Powered, Without $3K/kW Incentive	PEM Fuel Cell-Powered, With $3K/kW Incentive
Net Present Value of Capital Costs	$ 17,654	$23,835	$16,684
Net Present Value of Operations and Maintenance Costs (including fuel costs)	$127,539	$52,241	$52,241
Net Present Value of Total Costs of System	$145,193	$76,075	$68,925

Notes:

1. Based on: Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane (PEM) Fuel Cell Markets*, April 2007.
2. Assumptions: Operate 7 hours/shift, 3 shifts/day, 7 days/week; batteries changed out every shift, taking about 30 minutes; operator cost $15/hour; PEM fuel cell forklift uses 3 kW stacks with NiMH batteries; stack replaced every 5 years at $3,000/kW; batteries replaced every 5 years at $1,800/kW; PEM fuel cell forklift refueled once every shift, refueling time 1 minute; no disposal costs were assumed for any of the technologies.
3. The Emergency Economic Stabilization Act of 2008 includes a fuel cell investment tax credit that is equal to 30% of the qualified fuel cell property, not to exceed an amount equal to $1,500 for each 0.5 kW of capacity of such property.

Table 2. **Estimated lifecycle cost comparison of battery and PEM fuel cell backup power systems.**

	5kW Outdoor Installations		
	Battery/Generator	PEM Fuel Cell Without Incentive	PEM Fuel Cell With $3K/kW Incentive
52-hour run time	$61,082	$61,326	$46,326

Notes:

1. Based on: Battelle Memorial Institute, *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets* (April 2007).
2. Total cost includes capital costs and operations and maintenance costs.
3. Assumes 5-year battery replacement schedule. Analysis of 3-year replacement schedules (for cold or harsh environments) indicates PEM fuel cells compare more favorably to traditional technologies.
4. The Emergency Economic Stabilization Act of 2008 provides for an investment tax credit for fuel cells of $3,000/kW or 30%.

generators operating on diesel, propane, or gasoline; most backup power communication and control systems use a combination of generators and batteries to provide redundancy in order to avoid service disruptions. Although these systems are reliable and well-established, concerns with batteries and generators are encouraging customers to seek out alternatives that provide high reliability and durability at a reasonable cost. Compared to batteries, fuel cells offer longer continuous run-time and greater durability in outdoor environments under a wide range of temperature conditions. With fewer moving parts, they require less maintenance than both generators and batteries. They can also be monitored remotely, reducing actual maintenance time. Compared to generators, fuel cells are quieter and have no emissions. As Table 2 indicates, fuel cells can also offer significant cost advantages over both battery-generator systems and battery-only systems when shorter run-time capability of up to three days is sufficient.

Public and Private Adoption of Fuel Cells

Other types of fuel cells, including molten carbonate fuel cells (MCFCs) and phosphoric acid fuel cells (PAFCs), suitable for combined heat and power applications are also commercially available to provide electricity at critical load facilities including hospitals, data centers, and banks. In these applications, fuel cells can provide high-quality, reliable, grid-independent, on-site electric power, with reduced emissions compared to conventional power technologies.

Grocers, banks, tire and hardware companies, logistics providers, and others in the private sector have begun to recognize the value of using fuel cells to support their operations. The DOE is working in partnership with other federal agencies to identify opportunities for incorporating fuel cells into government operations as well. Early federal adoption not only shows the public that hydrogen and fuel cells are real and no longer confined to the laboratory, but it also proves the government takes its leadership role seriously – that agencies are incorporating into their own operations clean, energy-efficient, advanced technologies (including fuel cells) that will reduce our nation's dependence on oil as well as greenhouse gas emissions and criteria pollutants.

In addition to achieving societal benefits, early federal adoption can support commercialization and industry growth by affecting fuel cell cost reduction. A recent study released by Oak Ridge National Laboratory found that implementing a government acquisition program focused on fuel cells for backup power and specialty vehicles/lift trucks would result in manufacturing

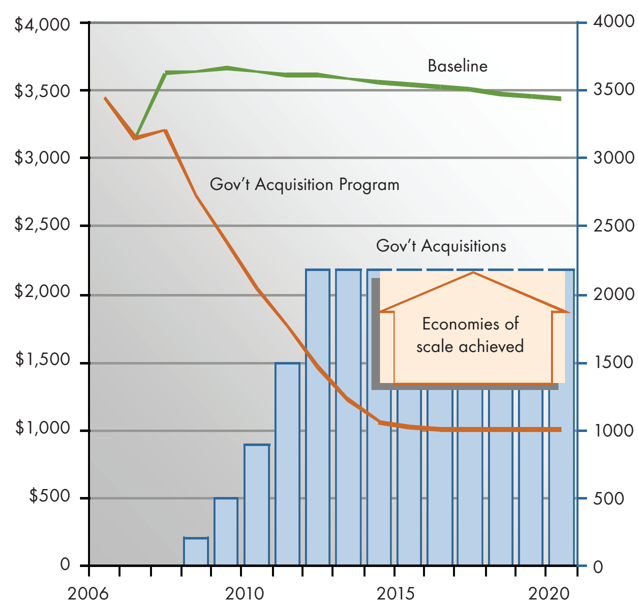

Figure 1. **Estimated impact of government acquisitions on fuel cell stack costs.[11]**

economies of scale that could enable fuel cells to be cost competitive with conventional technologies, such as batteries and small combustion engines.[10]

Unlike other alternative fuels and advanced technologies that benefit from a history of deployment activity, however, hydrogen and fuel cells are new to federal energy managers. Enabling early adoption, therefore, requires a combination of technical and financial assistance, data collection, and communications and outreach. In addition to identifying ways in which the DOE can incorporate fuel cells into its facilities – potentially to support data center operation and national laboratory critical load needs – the program seeks to facilitate early adoption of hydrogen and fuel cell technologies among other federal agencies. Working through an interagency task force and working group, the program has facilitated partnerships with other agencies. These partnerships help identify deployment opportunities in key early markets, provide financial assistance through cost-shared agreements, and offer technical expertise to support competitive procurements as well as use third-party financing to take advantage of the fuel cell investment tax credit and other policy incentives that can minimize the government outlay for fuel cell projects.**

These partnerships have resulted in projects that will provide valuable data on the status of the technologies in real-world operation and information that will be used to validate the benefits of the technologies. Notable efforts include the following:

- The Defense Logistics Agency's effort to place approximately 100 forklifts at its distribution centers across the country.
- The Department of Defense's planned installation of 18 fuel cell systems that provide backup power to military installations in California and South Carolina.
- The US Postal Service's operation of two fuel cell vehicles in regular mail delivery service.
- The Federal Aviation Administration's planned installation of approximately 25 additional fuel cell back-up power systems at remote telecommunication towers.

Similar to the vehicle demonstrations, data collected through these efforts will be made available as composite data products, giving other potential users important information about the technology's performance in practical, real-world operation.

CONCLUSION

Together with its partners, the DOE plans to continue building on recent progress. For more information about hydrogen and fuel cells, DOE Hydrogen Program activities, and upcoming events, please visit www.hydrogen.energy.gov.

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* Transportation fuels are often compared on their equivalency to gasoline. The amount of fuel with the energy content of one gallon of gasoline is referred to as a gallon gasoline equivalent, or gge.

† Distributed reforming refers to the generation of hydrogen on a small scale at or near the point of use. For instance, rather than generating hydrogen on a large scale and transporting it from a centralized location, the hydrogen required for fuel cells can be generated on-site.

‡ The costs of $275/kW and $73/kW are based on 2002 and 2008 dollars, respectively. The 2015 target of $30/kW is based on 2002 dollars.

§ The Emergency Economic Stabilization Act of 2008 includes a fuel cell investment tax credit (ITC) of $3,000/kW or 30%; for more information, see www.usfcc.com/ITC-TaxQA10-2008%20_2_.pdf.

** The Hydrogen and Fuel Cell Interagency Task Force, established by Section 806 of the Energy Policy Act of 2005, includes senior-management level representatives of federal agencies and is focused on demonstration and deployment; the staff-level Hydrogen and Fuel Cell Interagency Working Group coordinates hydrogen and fuel cell research and development activities across the federal government.

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[11] Greene, D.L. and K.G. Duleep, "Bootstrapping a Sustainable North American PEM Fuel Cell Industry: Could a Federal Acquisition Program Make a Difference?" October 2008.

Ms. Christy Cooper is responsible for communications activities and supports market transformation activities for the Hydrogen, Fuel Cells and Infrastructure Technologies Program in the Department of Energy's Office of Energy Efficiency and Renewable Energy. In this capacity, she is part of a new and growing Program effort to advance the use of hydrogen fuel cells in key early markets including material handling equipment, backup power, and primary power, as well as integrated renewable hydrogen energy systems. Ms. Cooper previously served as the Program's Education team lead and was responsible for a broad range of education and training activities for safety and code officials, state and local government representatives, local communities, and potential end-users, as well as university and other student programs. She currently serves as a co-chair of the International Partnership for the Hydrogen Economy Education Work Group and manages DOE's activities in its capacity as co-chair of the Interagency Hydrogen and Fuel Cell Working Group. Ms. Cooper began her career at DOE's Office of Energy Efficiency and Renewable Energy in 1995 with the Clean Cities Program, a market development program for alternative fuel vehicles. There she was responsible for new coalition development and communications and outreach activities. She also managed the Fuel Economy Information Program and fueleconomy.gov.

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Hydrogen Storage Solutions in Support of DoD Warfighter Portable Power Applications

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BACKGROUND

From Personal Digital Assistants (PDAs) to cell phones our high-tech world is demanding smaller, lighter weight and higher capacity portable power devices. Nowhere has this personal power demand been more evident than in today's US warfighter. The modern warfighter is estimated to carry from 65 to 95 pounds of supplies in the field with more than 30 pounds of this dedicated to portable power devices.[1] These devices include computer displays, infrared sights, global positioning systems (GPS), night vision and a variety of other sensor technologies. More than 80% of the energy needed to power these devices comes from primary (disposable) batteries. It is estimated that a brigade will consume as much as seven tons of batteries in a 72-hour mission at a cost of $700,000.[2]

A recent comprehensive study on the energy needs of the future warrior published by the National Academy of Sciences in 2004 made a variety of recommendations for average power systems from 20 to 1,000 watts.[3] For lower power systems recommendations included pursuing science and technology initiatives focused on 1) secondary (rechargeable) battery technologies with an energy density of 300 watt-hour per kilogram (Wh/kg),* 2) hybrid power sources, and 3) fuel cells (with greater than 6 wt% hydrogen storage).

Improved secondary batteries may be the ideal solution for military power systems due to their ease of use and public acceptance. However, 300 Wh/kg represents a two-fold improvement in specific energy density and that is not likely anytime soon. Current lithium-ion (Li-ion) batteries, at about 150 Wh/kg, fall well short of the energy density that is required. Future battery technology may not be a viable solution since many experts do not predict more than a two-fold improvement in Li-ion battery systems over the next 10 years.[4] Thus, most auto companies have abandoned all electric vehicles in favor of fuel cells and hybrid vehicles.

Hybrid systems typically combine low energy and high power components with high energy and low power components. Typical configurations include capacitors and fuel cells or batteries and fuel cells. A hybrid system can have both high energy and high power density; if combined effectively, these components can work synergistically to provide greater amounts of energy and power than the individual components.

Fuel cells have very high specific energy densities but achieving high energy values will depend on the energy density and the storage method of its fuel. Improved methods of safely and efficiently storing larger amounts of hydrogen will be a key development area for portable fuel cell power systems.

For fuel cells and hybrid systems to become more practical for common applications, the storage of hydrogen must first be addressed. This paper describes advanced hydrogen storage materials being developed by Savannah River National Laboratory (SRNL) and other related Department of Energy (DOE) programs. The article also identifies leading candidates and systems that can be applied to DoD portable power applications. The plans and initial activities of a new DoD Warfighter Portable Power Center located at the Center for Hydrogen Research are also described.

HYDROGEN

Hydrogen at 33,000 Wh/kg has one of the highest specific energy densities of any other fuel; it is almost three times greater than the specific energy density of gasoline. For many applications the specific energy density or the amount of energy per unit weight of the fuel is often critical. This is especially true in warfighter and other man-portable power applications where weight of the entire system needs to minimized. Table 1 compares the specific energy density of various fuels.

Hydrogen is a high energy fuel, and it is often used as NASA's fuel of choice for rockets and space exploration platforms. Another advantage of hydrogen is its higher energy conversion efficiency (i.e., the ratio between the useful output and the input) when used in a fuel cell (50-60%) compared to the efficiency of an internal combustion engine (15-25%). This would allow a soldier in the field to obtain two to four times more energy from hydrogen than can be obtained by converting the same amount of energy from another fuel to useful work. With 6 wt%† storage and a 50% energy conversion efficiency, a hydrogen fuel cell system could generate an energy density of 1000

Table 1. **Specific energy density of various fuels.**

Fuel	Specific Energy Density, Wh/kg
JP-8 and Gasoline	12,000
Methanol	5,600
Ethanol	7,500
Hydrogen	33,000
Hydrogen (6%)	2,000

Table 2. Comparison of various soldier power systems.

Technology	Specific Energy Density, Wh/kg	Average Power, W
Fuel Cell/H_2 (5000 psi)	1,033	20
Fuel Cell/$NaBH_4$	556	20
Direct Methanol Fuel Cell	478	20
Li-ion battery*	170	20
Fuel Cell/H_2, 6%	659	100
Direct Methanol Fuel Cell	581	100
Li-ion battery*	170	100

*State-of-the-Art

Wh/kg or almost seven times that of current Li-ion batteries. For example, a recent DoD challenge sought the development of a 20 watt warfighter system that lasts through a 96-hour mission and weighs less than 4 kg (see article titled "Lightweight Wearable Power Energized by Pentagon's Prize Program" on page 11.) This requirement can be restated as a power system with a specific energy density of 500 Wh/kg. Table 2 compares several soldier energy sources for 20 W and 100 W average power for 72-hour missions.[3]

From Table 2, it can be seen that several fuel cell systems using either direct hydrogen, metal hydride or direct methanol all have the ability to achieve system energy densities in excess of 500 Wh/kg. Also all of the fuel cell systems have specific energy densities three to five times that of the latest Li-ion secondary battery technology. By further increasing the hydrogen storage density in these fuel cell systems to 10 wt% or higher, it could easily lead to systems with energy densities in excess of 1000 Wh/kg.

While hydrogen has a very high specific or gravimetric energy density, the opposite is true with respect to its volumetric energy density or the amount of energy per a given volume of fuel in watt-hour per liter (Wh/l). As a gas, hydrogen must be compressed to pressures of 5000 pounds per square inch (psig) or higher to obtain a reasonable volumetric energy density. Even liquefied hydrogen only has a volumetric energy density about a fourth of that of gasoline. Hydrogen storage technologies thus become key to the successful application of hydrogen technology. Research on more efficient ways of storing hydrogen, at even higher volumetric densities than liquid hydrogen, is actively being pursued all over the world for a variety of power applications ranging from automobiles to laptops.

HYDROGEN STORAGE

The Savannah River National Laboratory has been working with the DOE, other national laboratories, universities and industry to develop high capacity, low weight hydrogen storage materials for automotive applications. This has often been referred to as the hydrogen "Grand Challenge". The goal of the DOE Hydrogen Program is to develop onboard hydrogen storage for passenger vehicles that achieves greater than a 300-mile driving range without compromising passenger/cargo space, performance or cost. This requires meeting targets which include: hydrogen capacity, operating temperature range (-40 to +85°C), hydrogen supply rate/refueling rate (0.2 grams of hydrogen per second per kilowatt of power and refueling time less than three minutes for five kg of hydrogen), system cost, fuel cost, safety, reliability, cycle life, efficiency, etc.[5]

Over the past several years, while many new materials have been developed under the DOE program, most have fallen short of the challenging automotive-based targets. Figure 1 shows the current status of the DOE program with respect to the gravimetric and volumetric targets. Because hydrogen exists as such a lightweight gas, storing it at a high gravimetric and volumetric density has been one of the greater hydrogen storage challenges. From Figure 1, the DOE system targets of 45 grams per liter (g/l) and 6 wt% hydrogen and 80 g/l and 10 wt% hydrogen for 2010 and 2015, respectively, are represented by the box in the top right hand corner of the graph. Also in Figure 1 some preliminary system results for various hydrogen storage materials are plotted and compared to compressed and liquid hydrogen systems. It is obvious from Figure 1 that none of the materials developed to date, including compressed gas and liquid hydrogen, meet the current DOE capacity targets when compared on an overall system basis.

To help attain their hydrogen storage goals, DOE has funded three multi-disciplinary Centers of Excellence in hydrogen storage materials development and a new Center of Excellence in hydrogen storage engineering and systems development. The three materials centers in Metal Hydrides, Chemical Hydrides and Adsorbents are all led by various DOE National Laboratories with participation by various university, industrial and other federal laboratory partners. SRNL has recently been selected by the DOE to lead the new Hydrogen Storage Engineering Center, which is tasked to work with the other three centers to develop and test subscale engineered systems of the most promising candidate hydrogen storage materials.

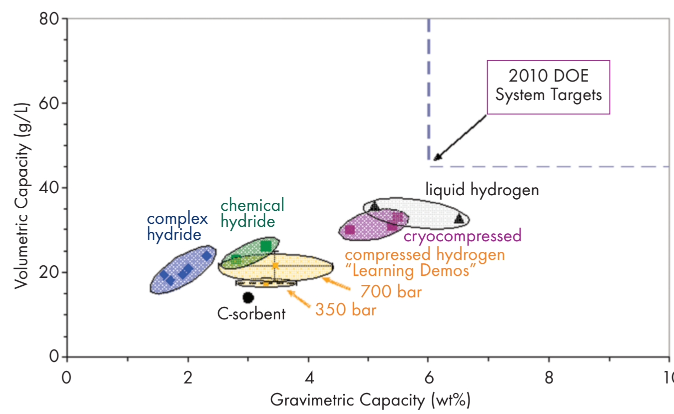

Figure 1. Current status of DOE hydrogen storage targets.[5]

Hydrogen Storage Engineering Center
http://www1.eere.energy.gov/hydrogenandfuelcells/storage/index.html

While the DOE hydrogen storage challenge is still moving forward, based on automotive requirements SRNL believes that many of the new materials that have been developed may already have potential for portable power applications. For example, many portable power applications do not require the same cost targets that are required by the transportation marketplace. Also options like fuel cartridge swapping and replacement are much more suitable and economical for smaller portable power systems than for onboard vehicle systems.

Table 3 shows some of the high capacity hydrogen storage

Table 3. High capacity hydrogen storage materials.

Formula	Weight % Hydrogen
NH_3BH_3	19.6 (12% practical)
$LiBH_4$	18.3 (requires high temperatures)
$Al(BH_4)_3$	16.8
$Mg(BH_4)_2$	14.8
$LiAlH_4$	10.6
$NaBH_4$	10.6 (7.6% with 50% H_2O)
AlH_3	10.0
$NaAlH_4$	7.4 (5.6% practical)

materials that are being investigated by SRNL and the other centers for the DOE hydrogen storage program. While many of these appear to have the potential to meet the DOE 2010 system target of 6 wt% hydrogen, most cannot meet many of the other DOE targets because of their high operating conditions (e.g., temperature and pressure) or associated costs, which make them unsuitable for onboard passenger vehicle systems. Many of these candidate materials with hydrogen capacities from 10 to almost 20 wt% may be ideal candidates for military portable power applications, leading to system specific energy densities of 1500 to 3000 Wh/kg.

Many of the materials in Table 3 have a high volumetric hydrogen capacity. For example Alane (AlH_3) has twice the hydrogen capacity of liquid hydrogen, making it a good potential candidate for portable power systems. Some of the systems in Table 3 can simply be heated to release some or all of their hydrogen, while others can be slowly reacted with water or other liquids to release their contained hydrogen as well as some of the hydrogen from the water reagent. Sodium borohydride ($NaBH_4$) is an example of this type of material; when combined with a catalyst, it can react with water to provide hydrogen. $NaBH_4$ has already found some uses in military and other portable power applications.

Many of the hydrogen storage materials being developed in the US are being carried out under the DOE's National Hydrogen Storage Project, which includes independent projects and Centers of Excellence (CoEs) in applied hydrogen storage R&D as well as DOE Office of Science basic research in hydrogen storage.[5] Two of the materials centers that are actively involved in exploring materials, such as those described in Table 3, are the Metal Hydride Center of Excellence (MHCoE) and the Chemical Hydrogen Storage Center of Excellence (CHSCoE). Both centers are tasked to develop hydrogen storage materials that meet system targets for automotive hydrogen storage applications.

The MHCoE is primarily focused on metal and chemical hydride materials that can be recharged with hydrogen under conditions that are compatible with onboard vehicle operations. These materials are typically referred to as reversible hydrides. Some of the materials being investigated by the MHCoE include several boron (B) and aluminum (Al) based materials that have theoretical hydrogen capacities ranging from 7 to 18 wt% hydrogen (see Table 3). Despite their high hydrogen capacity many of these materials have not yet been shown to be fully reversible under conditions that are compatible with onboard vehicle storage. Some of these materials like $NaAlH_4$ have been found to be only partially reversible and some like $LiBH_4$ require over 500°C to release its hydrogen, which is too high a temperature for practical automotive applications. Another material being examined by SRNL and others in the MHCoE is AlH_3. This material is able to readily release 10 wt% hydrogen at practical conditions but it requires more than 100,000 atmospheres of pressure to recharge it with hydrogen. SRNL and Brookhaven National Laboratory have both been working on different ways to recharge and reform this material and so far have shown some success using both electrochemical and chemical synthesis methods, respectively.[6]

While the materials being developed by the CHSCoE are similar to those being examined by the MHCoE, the focus of the CHSCoE is to develop non-reversible chemical hydride materials. These are materials that would give up their hydrogen on board an automobile but then the material itself would have to be removed from the vehicle to be recharged by a chemical process. One of the early materials developed by the CHSCoE was sodium borohydride ($NaBH_4$). This material has found its way into several military portable power applications but was found not to be practical for vehicle applications. Today the CHSCoE is primarily focused on Ammonia Borane (NH_3BH_3), a material with a high 20 wt% theoretical hydrogen capacity. Work at the CHSCoE is mainly aimed at improving the quantity and rate of hydrogen released at the lowest temperatures possible and developing more energy and chemically efficient methods to regenerate the spent fuel.[7]

In addition to the efforts of the two Centers of Excellence described here briefly, there are many other US and international efforts underway to develop new efficient and high capacity hydrogen storage materials for automotive and other applications. The US DOE program has focused mainly on automotive applications and as a result many promising materials that may be appropriate for applications other than automobiles have not been pursued. SRNL has proposed the development of a new center that can leverage much of the work that has already been performed by DOE to provide the DoD, and eventually commercial market, with a reliable and lightweight portable power alternative.

DOD WARFIGHTER PORTABLE POWER CENTER

SRNL has proposed and is seeking FY10 funding for a unique Warfighter Portable Power Development Center focusing on 20-200 W soldier power systems. SRNL plans to team with

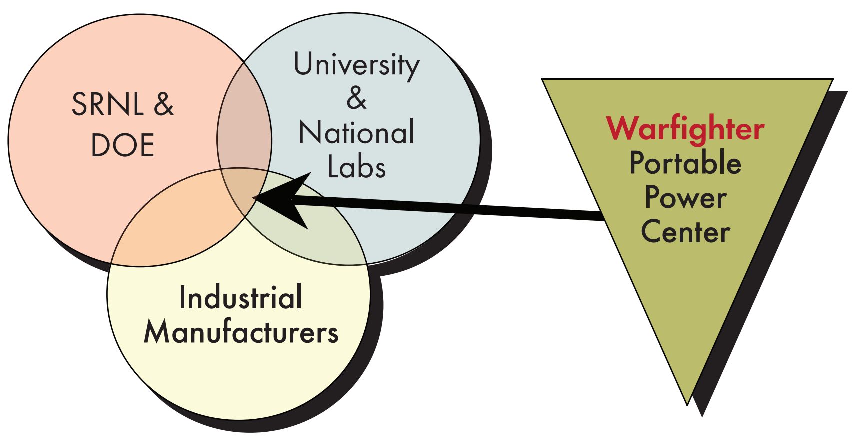

Figure 2. Warfighter Portable Power Center schematic.

universities, national laboratories and industrial partners to further enhance its already strong capabilities and talents. The unique feature of the proposed center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to join in integrating their components and devices into a final product, which functions as a complete military power pack – a system solution. Figure 2 shows a schematic of the proposed center's organization and its inter-relationships.

The driver for this type of center is twofold. First is the need to substantially increase the operational life and reduce the weight of battery packs often used by the military. The second driver is to leverage off of the many novel hydrogen storage materials and systems that are coming out of the DOE and other federal hydrogen programs. The goal of the center is to develop complete power source systems for a variety of portable warfighter applications. The primary approach of the center will be to identify several >10 wt% hydrogen storage systems and to combine them with fuel cells and other energy storage devices to arrive at an optimal power source solution. As described earlier, a fuel cell or a fuel cell hybrid portable power system with over 1000 Wh/kg is possible if a 10 wt% or higher hydrogen storage density material is available. During the first year of the center's operation a proof-of-concept system coupled with an existing military capable fuel cell will be demonstrated. Following a successful proof-of-concept, a field-ready prototype system could be developed with commercial partners during the next 12 to 18 months.

While increasing the specific energy density of warfighter

PARTNERSHIPS

The objective of the DOD Warfighter Portable Power Center is to partner with commercial fuel cell, battery, vessel and other component manufacturers as well as university and other national laboratory experts to develop and test complete power systems for military applications. To expedite this effort SRNL will partner with the Center for Hydrogen Research (CHR), a unique non-profit organization and facility located adjacent to SRNL facilities near Aiken, South Carolina. The role of the CHR is both to provide the creative environment and to serve as a catalyst to bring scientists and technologists from various organizations and disciplines together to help solve problems and develop unique solutions. The needs of the warfighter for high capacity and reliable power are an excellent example of the type of problems the CHR can address. The unique feature of the proposed center is its focus on inviting manufacturers and developers of fuel cells, batteries, capacitors and other electrochemical components and devices to partner in integrating their component parts and devices into a final product, which functions as a complete military solution.

The Center is aimed at providing the military with a complete solution to the future warfighter power needs.

The Center for Hydrogen Research

The CHR is a 60,000 square foot, $10 million facility designed for hydrogen research, development, and commercialization. CHR tenants include the Savannah River National Laboratory, Toyota Technical Center R&D lab, offices for the International Fusion Experiment project, and University of South Carolina - Aiken research on biohydrogen. The CHR and SRNL have under development a $1.0 million DOE-sponsored project to evaluate backup fuel cell power using metal hydride storage and electrolysis technologies. The CHR also operates a hydrogen refueling station and a hydrogen fueled internal combustion vehicle.

Savannah River National Laboratory

SRNL has more than 50 years of experience in developing and applying hydrogen technology, both through its national defense activities and its hydrogen energy activities with the DOE and industry. The hydrogen technical staff at SRNL comprises more than 90 scientists, engineers and technologists, and it is believed to be the largest such staff in the US. Forty of the SRNL hydrogen professionals have research facilities in the CHR. SRNL has ongoing R&D initiatives in a variety of hydrogen storage areas, including metal hydrides, complex hydrides, chemical hydrides and carbon nanotubes. SRNL has more than 25 years of experience in metal hydrides and solid-state hydrogen storage research, development and demonstration.

SRNL has been active in teaming with academic and industrial partners to advance hydrogen technology and has participated in projects to convert public transit and utility vehicles for operation on hydrogen fuel. Some major projects include the H2Fuel Bus and an Industrial Fuel Cell Vehicle (IFCV) also known as the GATOR™. Both of these projects were funded by DOE and cost shared by industry.

SRNL is a recognized international leader in hydrogen storage with added expertise in hydrogen production, fuel cells and battery technology. SRNL has excellent access to worldwide hydrogen technology information and is the DOE lead for the Hydrogen Storage Engineering Center of Excellence.

power systems is one of the main objectives of this program, another goal of the center is to optimize the power systems to military conditions and operations. These include improving their ease of use and reliability in the field and harsh environments, employing hybrid technologies to minimize the impact of using air breathing devices, minimizing heat and noise signals, and lowering overall system and deployment costs. The Warfighter Portable Power Center at the Center for Hydrogen Research would serve as catalyst and an incubator for the development, assembly and evaluation of future high energy military and eventually commercial portable power systems.

SUMMARY

The Savannah River National Laboratory with its primary partner the Center for Hydrogen Research has proposed a novel Portable Power Center aimed at supporting the DoD warfighter. The Center's objective is to leverage the current and past research on high capacity, hydrogen storage materials performed by SRNL and the other DOE National Laboratories for automotive applications. Some of these high capacity materials contain 10 to 20 wt% hydrogen but for one reason or another are not suitable for automobiles systems. However, many of these materials can still be viable for portable power systems. Combined with a small fuel cell these materials can lead to power packs that achieve specific energy densities of 1000 Wh/kg, more than 2 to 3 times that of today's best battery systems. The role of the new center will be to partner with industrial fuel cell, battery, other component manufacturers and system integrators to arrive at complete power solutions for the future warfighter.

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* *Energy density* is the amount of energy stored per unit mass.

† Weight percentage (wt%) hydrogen is the percentage of hydrogen by weight in the storage material compared to the weight of the overall storage material.

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Dr. Theodore (Ted) Motyka has a BS, an MS and a PhD all in Chemical Engineering. Dr. Motyka received his PhD degree from the University of Colorado in 1979 and then joined the Savannah River Site in 1980. Dr. Motyka is currently serving as the Hydrogen Program Manager for the Savannah River National Laboratory. During the past 15 years, Dr. Motyka and his team have been actively involved in the development and demonstration of hydrogen as an alternative energy carrier. Dr. Motyka has led several state initiatives for hydrogen energy, including an organization that produced the South Carolina Hydrogen and Fuel Cell Alliance. He is also responsible for initiating the new Center for Hydrogen Research in Aiken County. Recently, Dr. Motyka and his colleague Dr. Donald Anton were named as the Assistant Director and Director, respectively, of the new DOE Hydrogen Storage Engineering Center of Excellence for Hydrogen Storage.

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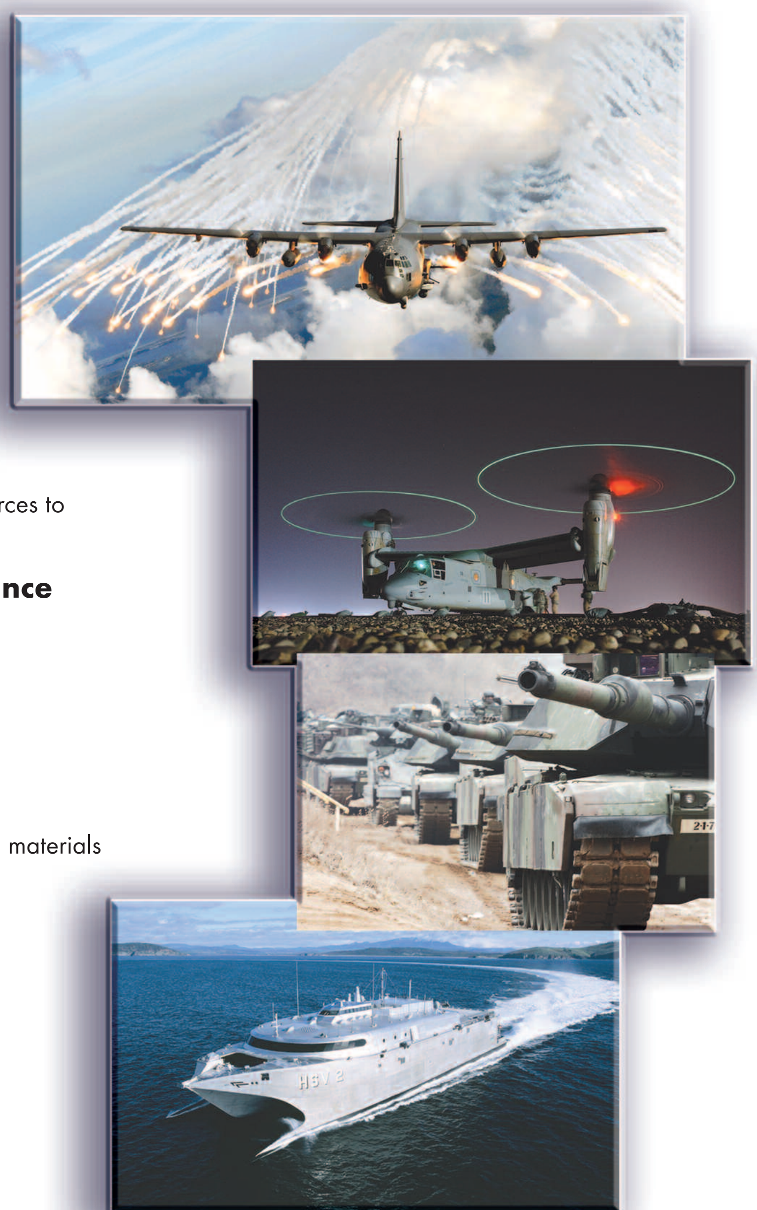

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